The Decay $\Sigma^+ \to p\,\mu^+\mu^-$ and Possible New Physics from HyperCP

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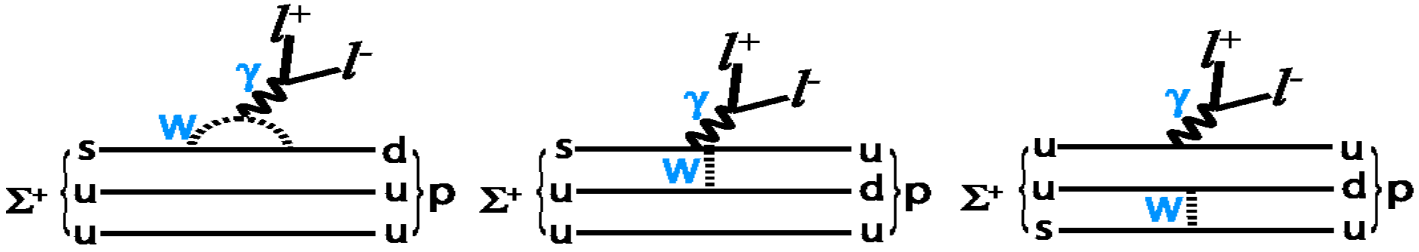
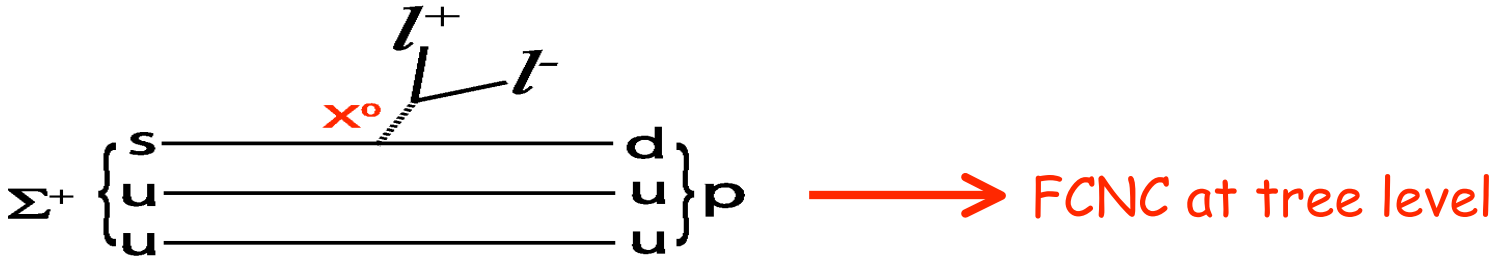
- Introduction
- Event Selection and background study
- Interpretations of the results
- Speculations
- Summary

Introduction and Physics Motivation (I)

- In SM, the decay $\Sigma^+ \rightarrow p\, l^+l^-$ (l=e μ) is described by these diagrams:



- Search for a new light scalar or vector particle:



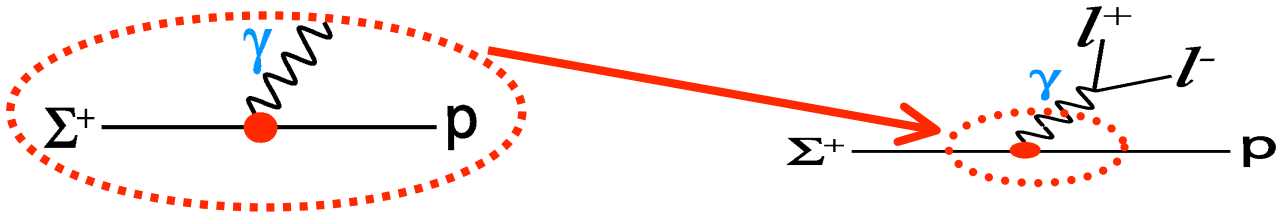
Extensions of SM usually predict a new scalar or vector particle.

Generally mass range for a new particle is model-dependent.

Note: This diagram would be distinguished by the dilepton mass distribution and branching ratio.

Introduction and Physics Motivation (II)

- Main uncertainty for the dilepton distribution and decay rate for the decay $\Sigma^+ \to p\, l^+ l^-$ is the hadronic matrix element, $\Sigma^+ \to p\gamma^*$.
- Use $\Sigma^+ \to p\gamma$ **decay** to reduce the theoretical uncertainty.



- The hadronic matrix element has 4 form factors: b_1, b_2, c_1 and c_2
- Form factors, b_1 and b_2, can be extracted from the decay rate and parameter for $\Sigma^+ \to p\gamma$:

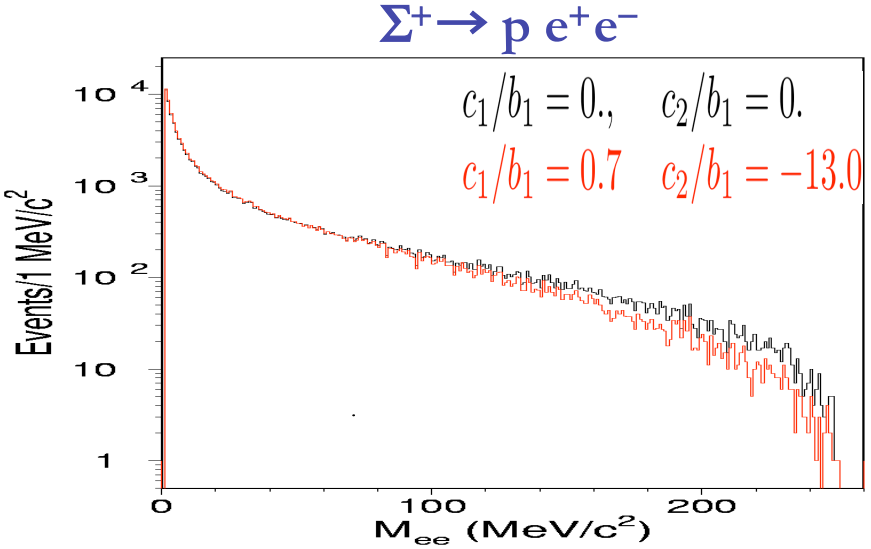
$$\Gamma(\Sigma^+ \to p\gamma) \propto (|b_1|^2 + |b_2|^2), \quad \alpha(\Sigma^+ \to p\gamma) = \frac{2\mathrm{Re}(b_1 b_2^*)}{|b_1|^2 + |b_2|^2}$$

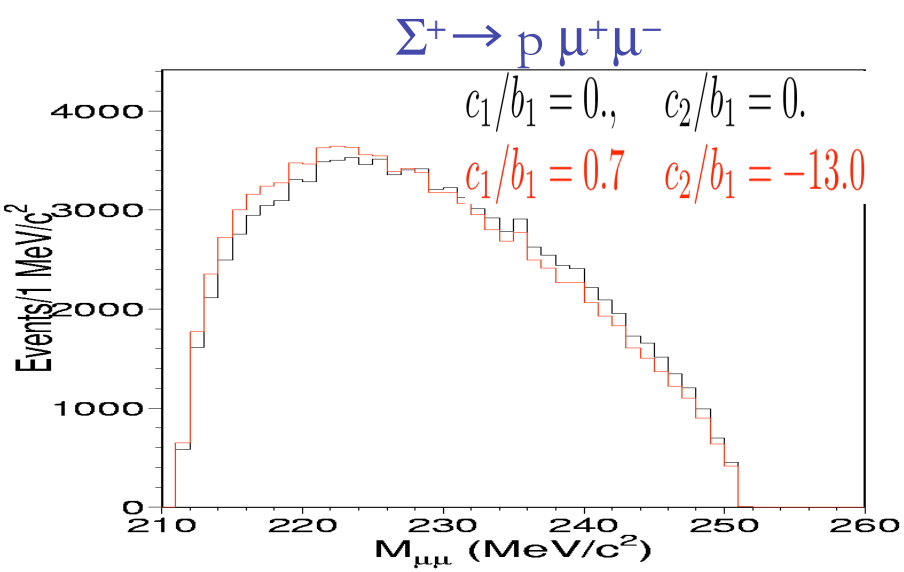
$$b_2(0)/b_1(0) = (-0.46 \pm 0.07), \quad |b_1(0)| = (6.8 \pm 0.2)\ \mathrm{MeV}$$

The limits on the form factor c_1 and c_2 are determined from the upper limit for $\Sigma^+ \to p\, e^+ e^-$.

Introduction and Physics Motivation (III)

- Dilepton distribution





- Theoretical prediction (L. Bergström, R. Safadi and P. Singer, Z. Phys. C **37**, 281 (1988))

$$\mathbf{B(\Sigma^+ \to p e^+ e^-) \sim B(\Sigma^+ \to p\gamma) \cdot \alpha_e\ (\sim 10^{-6})}$$ (back-of-envelop estimation)

$$\mathbf{B(\Sigma^+ \to p e^+ e^-) \gtrsim 8.9 \times 10^{-6}}$$

$$\mathbf{\frac{1}{1210} \lesssim \frac{\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{\Gamma(\Sigma^+ \to p e^+ e^-)} \lesssim \frac{1}{120}}$$

Violation of these limits → signal of new physics

or

Modification of form factors.

- Experimental result:

$$\mathbf{B(\Sigma^+ \to p e^+ e^-) < 7 \times 10^{-6}}$$

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Production of Secondary Beams

- P (800 GeV/c) + Cu → Secondary Particles
- Collimator (6.1 m) with 1.7 T of Dipole Magnetic Field
  - Bend charged particles upward or downward
    → Select either + or - particles
  - Central-Orbit Momentum: 170 GeV/c

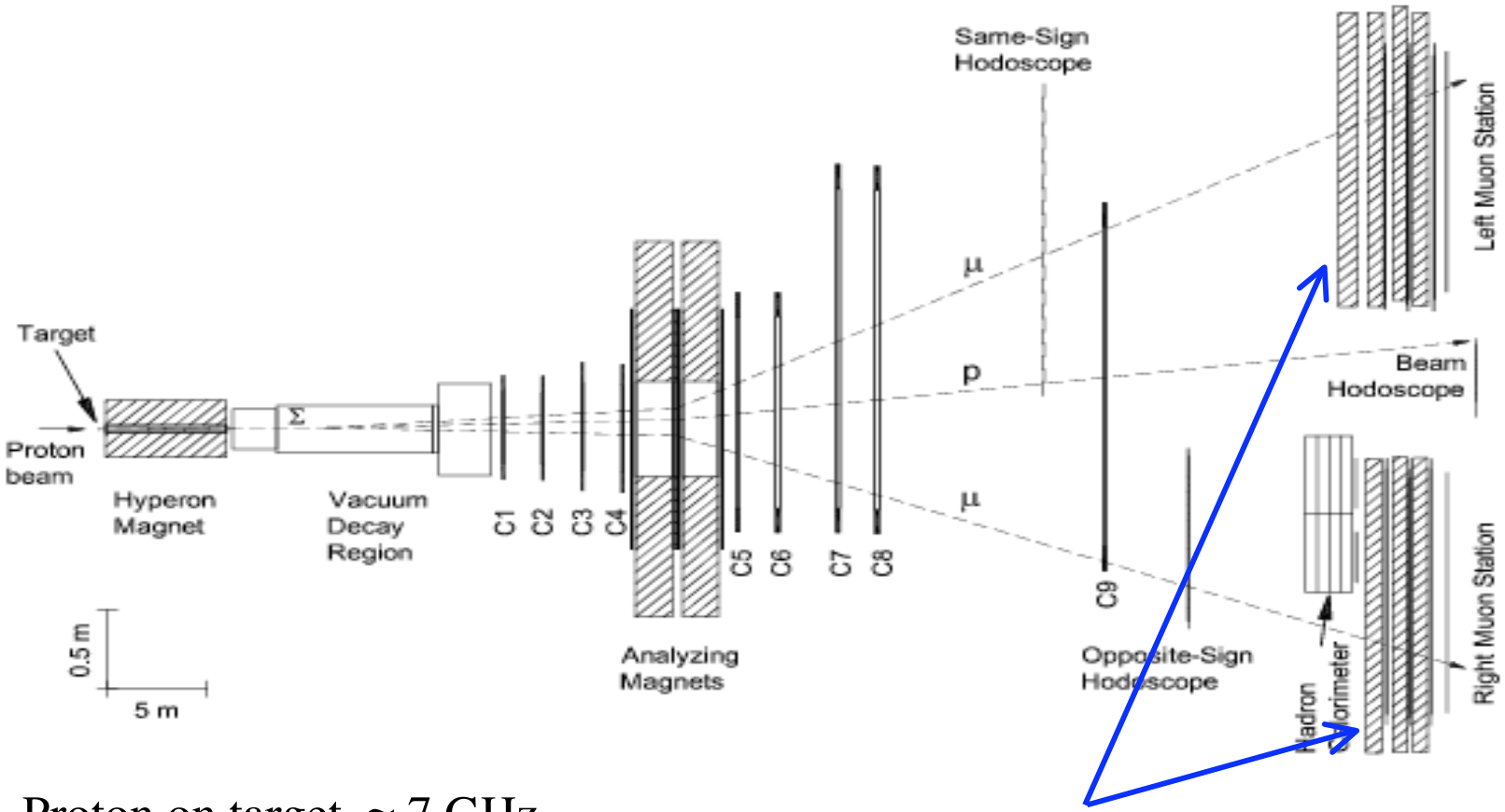
- Only long-lived charged particles exit from the Collimator:

Mainly $\pi^{\pm}, \mathbf{p}, \overline{\mathbf{p}}, \mathbf{K}^{\pm}, \boldsymbol{\Sigma}^{\pm}, \boldsymbol{\Xi}^{\pm}, \boldsymbol{\Omega}^{\pm}$

HyperCP Spectrometer

- 13 m vacuum decay region
- 9 fast narrow-pitch MWPC (36 planes)
- Analysis Magnet:
  Bend charged particles in horizontal direction
- Simple trigger using hodoscopes
  Left-Right trigger: Coincidence of the left- and right-side hodoscope hits
- Muon System: Only particle ID detector
  - Stations on left and right side
  - Total 3.2 (2.3) m-thick steel absorber in left (right) side
  - In each station: 3 layers of proportional tubes
    2 hodoscope planes for trigger
  - Accepted muon momentum: **> 20 GeV/c**

HyperCP Spectrometer



- Proton on target ≈ 7 GHz
- Secondary beam rate ≈ 13 MHz
- The typical run cycle: + + + - + + + -

Built by Univ. of Michigan

Summary of the 1997 and 1999 runs

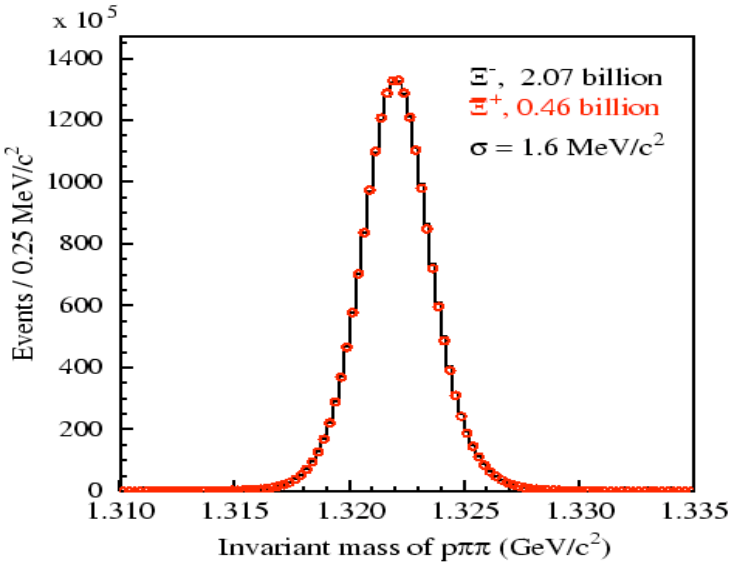
	1997 run	1999 run	Total
Number of tapes	8,980	20,421	29,401
Data Volume	38 TB	82 TB	120 TB

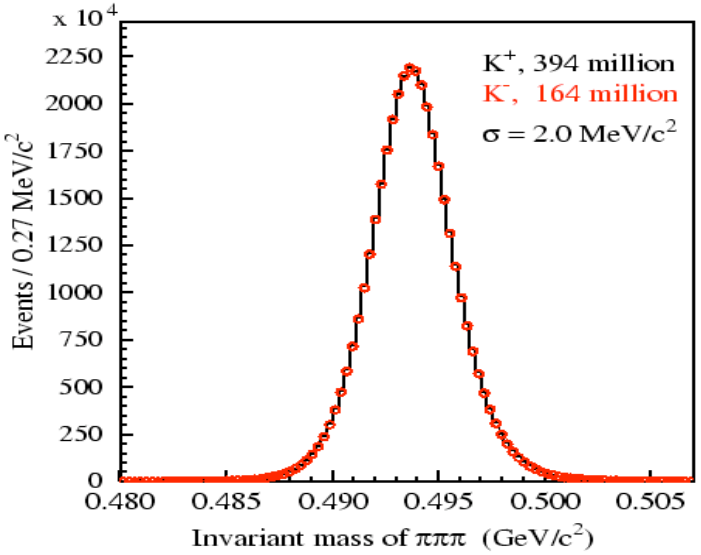
Number of reconstructed events

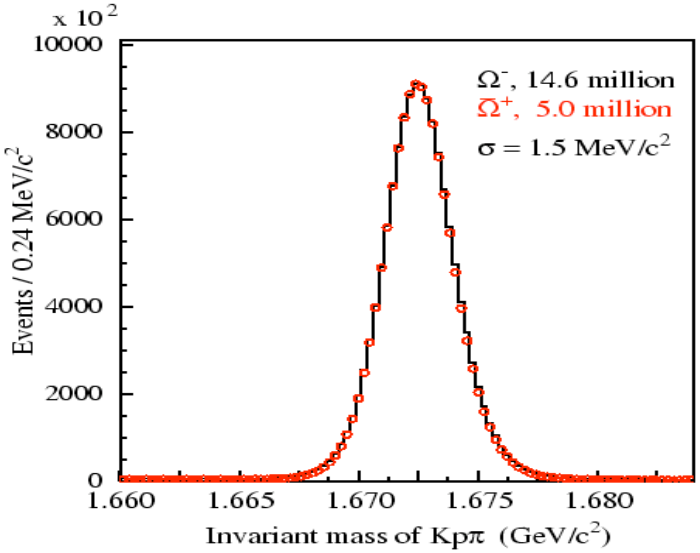
	Beam Polarity	
Decay	Negative	Positive
$\Xi \rightarrow \Lambda\pi$	2×10^9	0.5×10^9
$K \rightarrow 3\pi$	0.16×10^9	0.39×10^9
$\Omega \rightarrow \Lambda K$	15×10^6	5.0×10^6

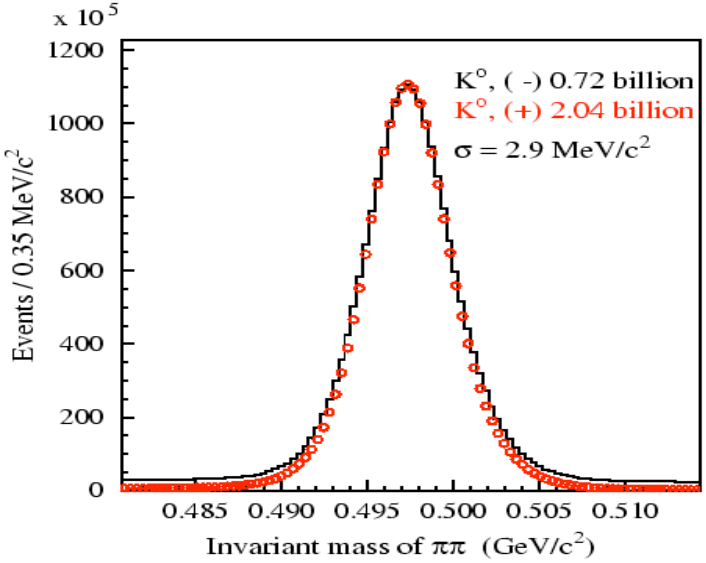
Σ^+ yield is ~10 times Ξ^-. Expect ~10^{10} Σ^+ decays.

Mass Plots from Total Sample









Data Analysis Strategy for $\Sigma^+ \rightarrow p\mu^+\mu^-$ (I)

- Use the positive and negative data set from '99 run.
  Split two exclusive samples: Dimuon and Signle-muon sample
- Muon selection:
  - Hits in 2 out of 3 proportional tubes in both x and y view.
  - Hits in both vertical and horizontal hodoscopes in the muon station
- Proton candidate selection:
  1. Any hadron track in left side
  2. For an event with more than one hadron track:
     One-vertex constrained χ^2 fit with two unlike-sign muon tracks

     Select the proton candidate having lower χ^2/ndf

- Dimuon sample for the signal search:
  - Two unlike-sign muons and proton candidate
  - Unlike-sign dimuon trigger prescaled by 1.

Data Analysis Strategy for $\Sigma^+ \rightarrow p\mu^+\mu^-$ (II)

- Single-muon sample for background study:
  - Only one track is tagged by the muon selection
  - Non-muon track:

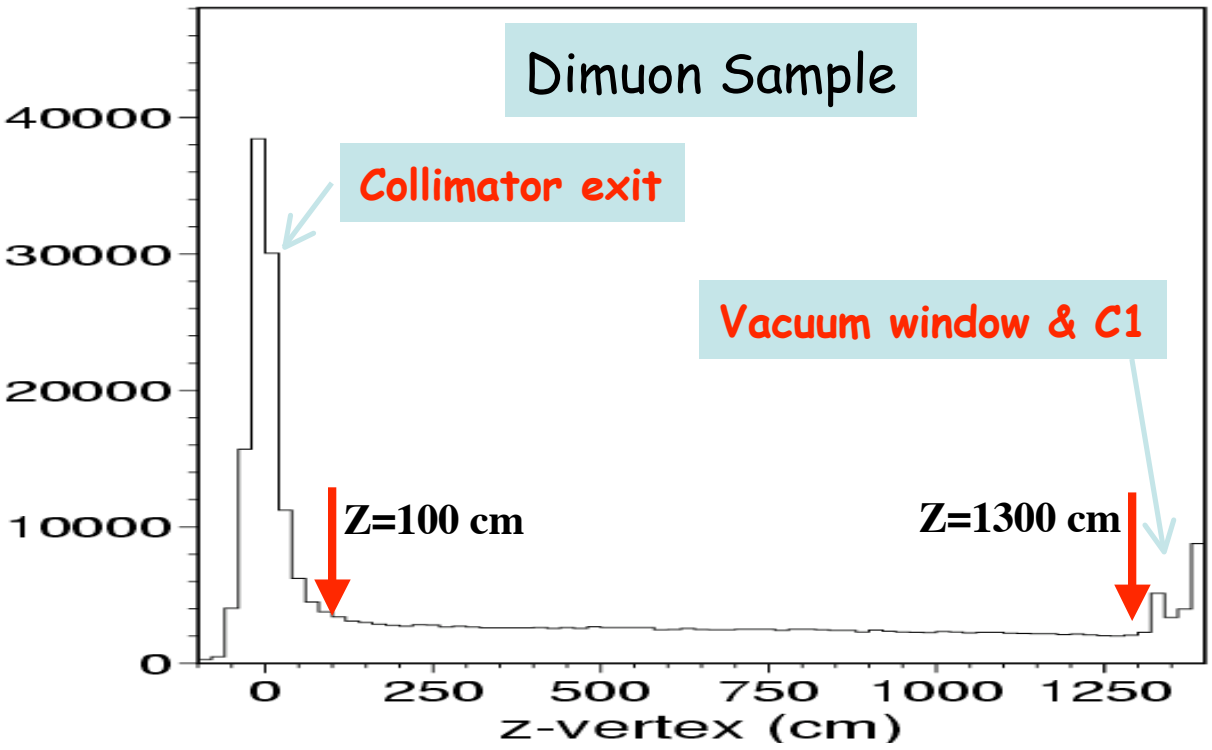
    Opposite-sign of the muon track.
    Within the fiducial volume of muon station.
  - Prescale factors for the single muon trigger:
    5 and 10 for the right- and left-side muon station, respectively.

    Do not expect the signal from the single muon sample.

- Use the basic selection and additional selection cuts
- Reconstruct mass with p μ^+ μ^- hypothesis

Basic Selection Cuts I
(z-vertex)

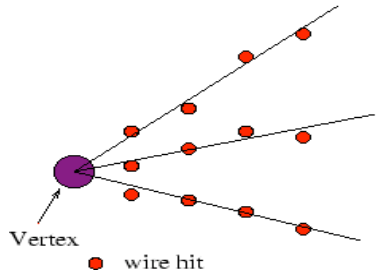
- Decay vertex within the vacuum decay pipe: **z-vertex**
  (Reconstruct z-vertex by the distance of closest approach.)



Basic Selection Cuts II
(single-vertex tagging)

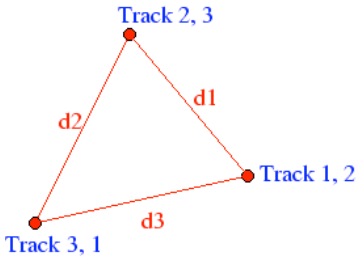
- Decay consistent with single vertex:

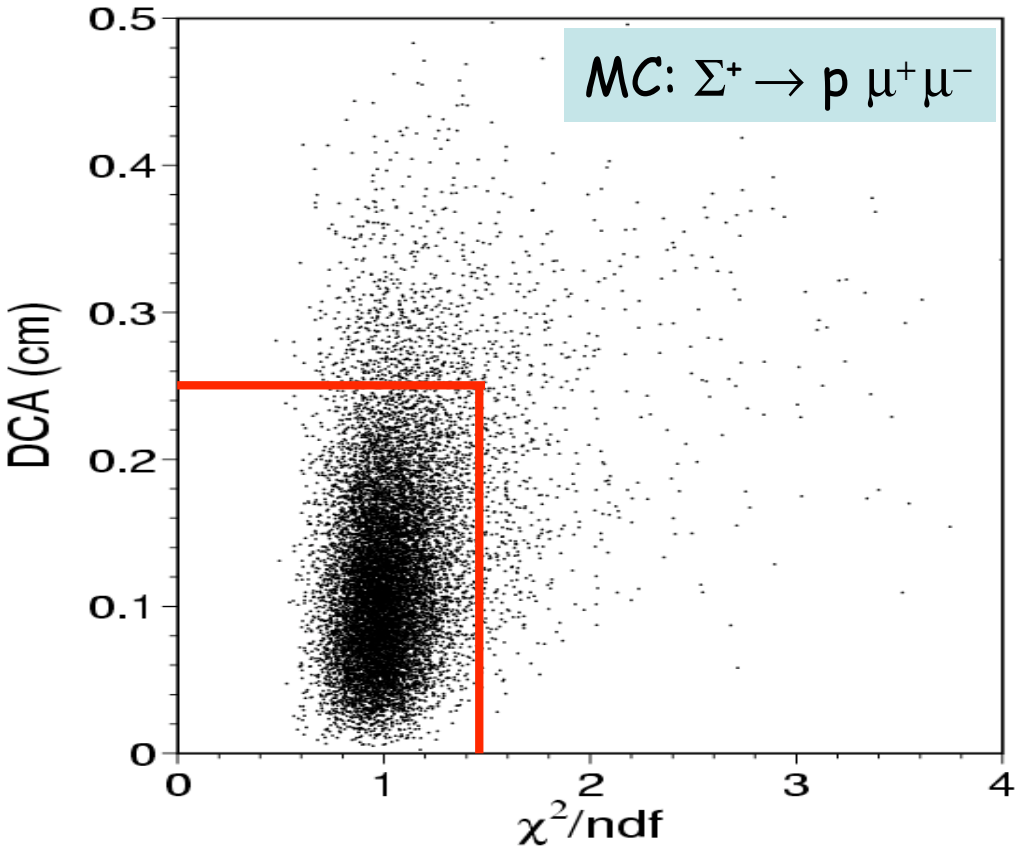
1) Good fit: χ^2/ndf



2) Lateral separation at z-vertex:

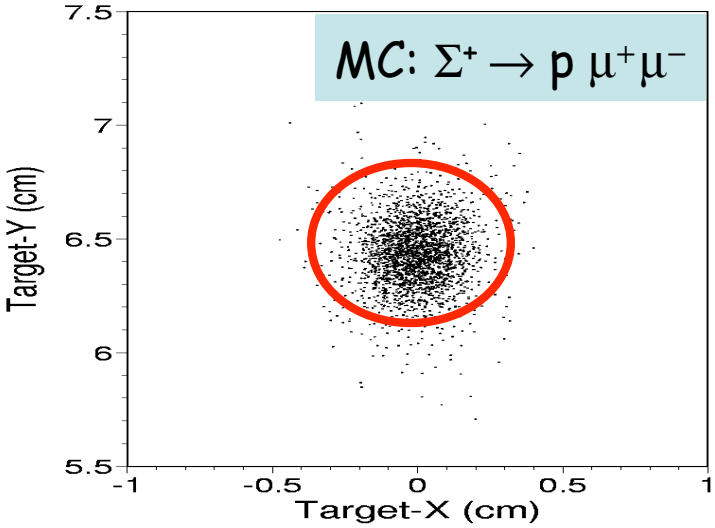
DCA=(d1+d2+d3)/3



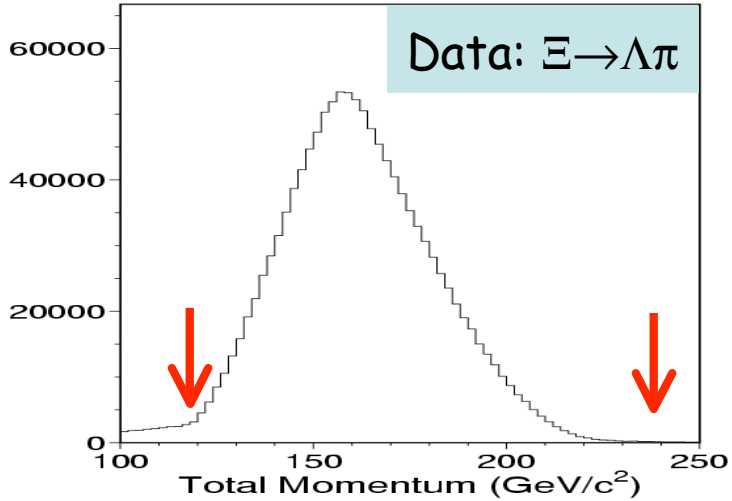


Basic Selection Cuts III
(Target Pointing and Total Momentum)

- The Σ^+ beam from the target:
  target pointing cut



- Momentum acceptance of the collimator:
  total momentum of 3 tracks



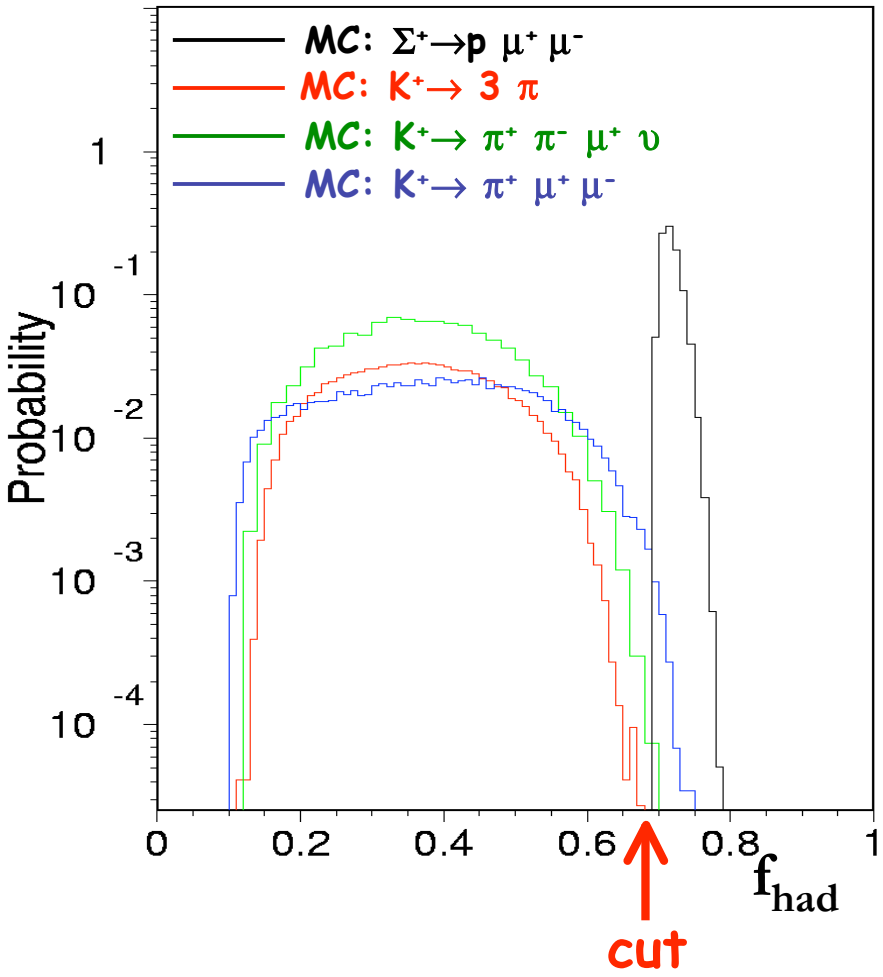
Additional Selection Cut

- Hadron momentum fraction cut:

$$f_{had} = \frac{\text{hadron momentum}}{\text{total momentum}}$$

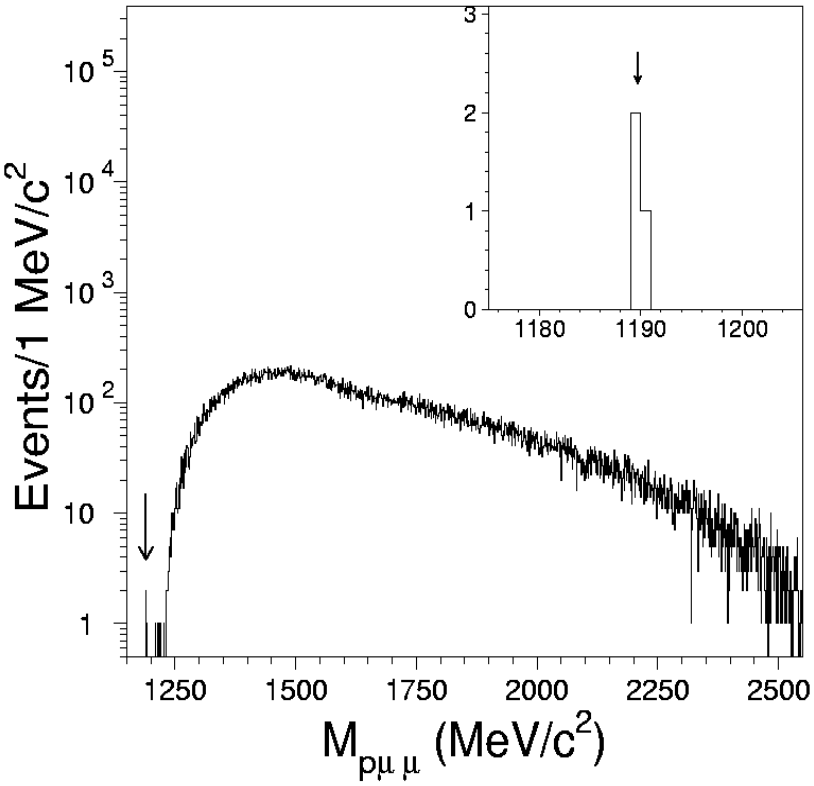
- Require $\mathbf{f_{had} > 0.68}$
  - Preserve 100% of the signal
  - Strong rejection of K^+ backgrounds

Decay Mode	ϵ (%)
$B(K^+ \to 3\pi) = 5.6\%$	0.0
$B(K^+ \to \pi^+\pi^-\mu^+\nu_\mu) = 1.4 \times 10^{-5}$	~0.0
$B(K^+ \to \pi^+\mu^+\mu^-) = 8.1 \times 10^{-8}$	0.4

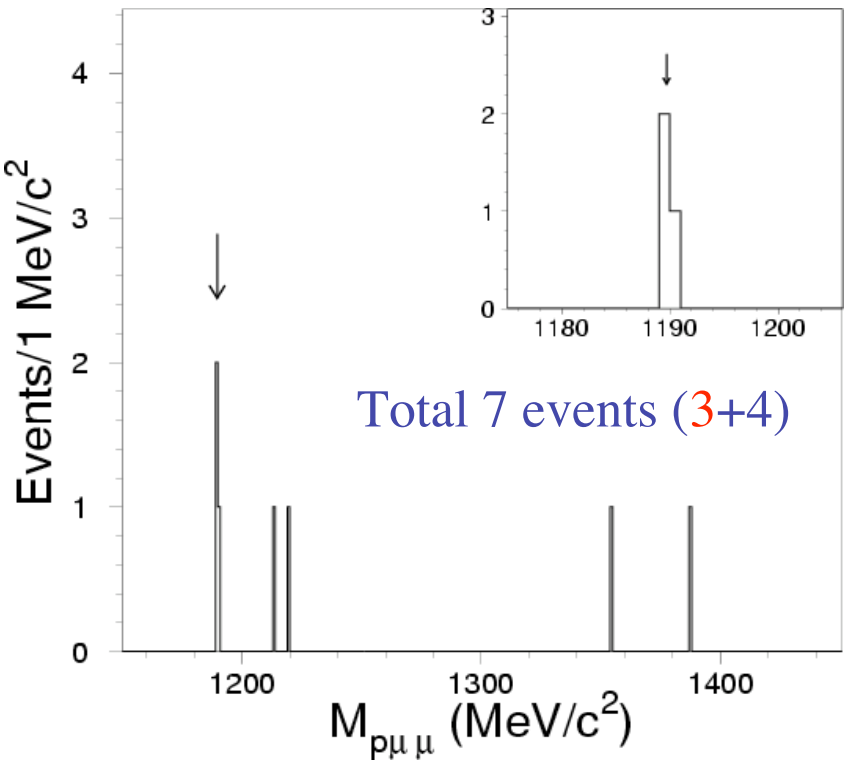


Event Selection for $\Sigma^+ \rightarrow p\mu^+\mu^-$ (Data)

Basic selection cut



Basic selection and f_{had} cuts

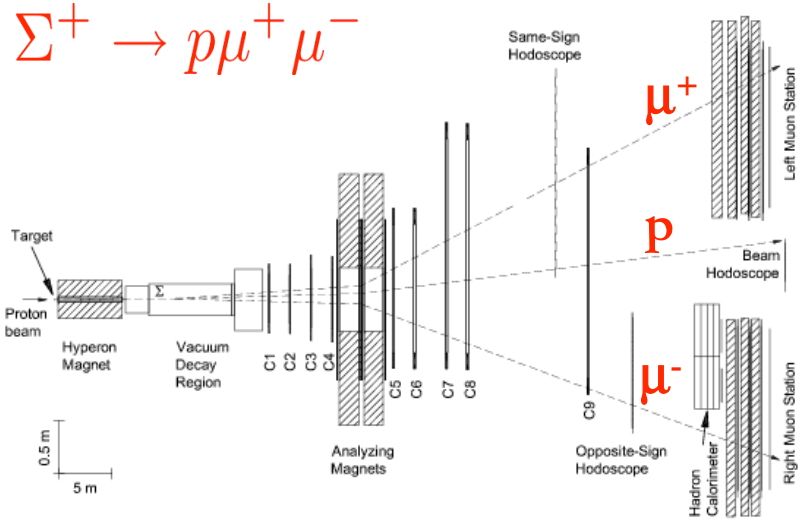


- Observed 3 candidates within 1 σ of mass resolution (1 MeV/c^2): only in positive-beam dimuon data.
- Background events were more than 20 σ from Σ^+ mass.

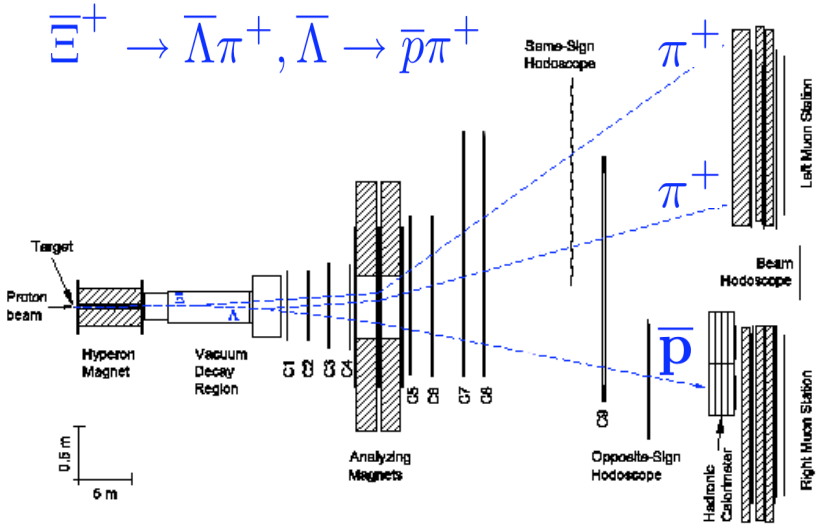
Background Study: Hyperon decays

- Ordinary hyperon decays contribute to like-sign dimuon events,
  e.g., pion or kaon decay from $\begin{cases} \overline{\Xi}^+ \to \overline{\Lambda}\pi^+, \overline{\Lambda} \to \bar{p}\,\pi^+ \\ \overline{\Omega}^+ \to \overline{\Lambda}K^+, \overline{\Lambda} \to \bar{p}\,\pi^+ \end{cases}$

$\Sigma^+ \to p\mu^+\mu^-$



$\overline{\Xi}^+ \to \overline{\Lambda}\pi^+, \overline{\Lambda} \to \bar{p}\pi^+$



Hyperon decays are not background

Background Study: K^+ decays (I)

- 1.0 x 10^{10} K^+ decays in positive-beam data
- Backgrounds from K^+ decays:

  $K^+ \to \pi^+\pi^+\pi^-$, $K^+ \to \pi^+\pi^-\mu^+\nu$

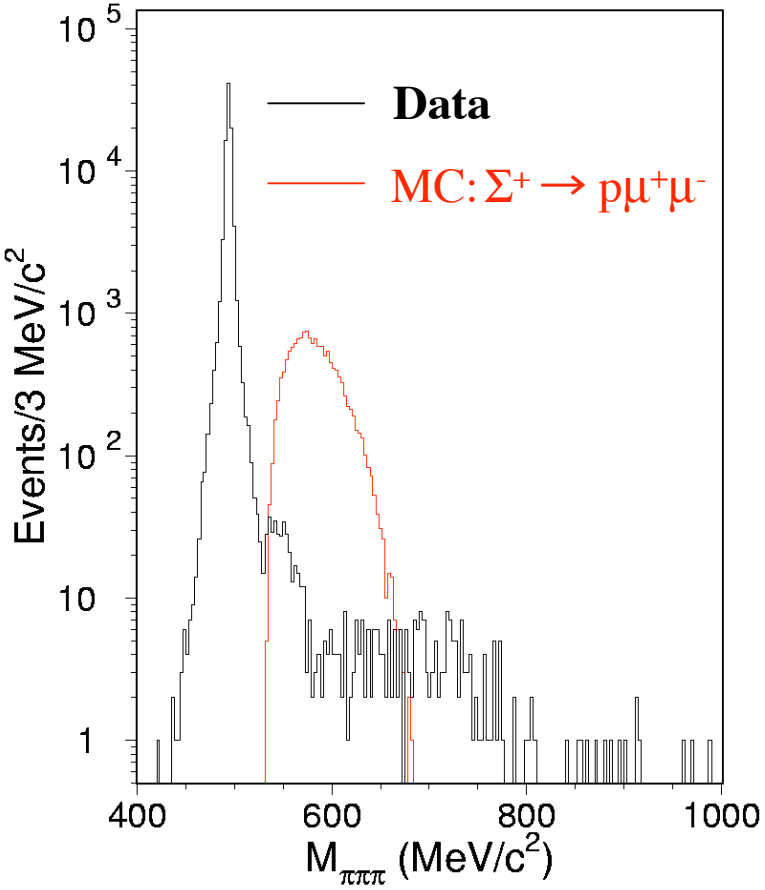
  $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \mu^+\mu^-\mu^+\nu$ **Not observed**

- In MC study, none of them are serious sources:

  Used 40 to 100 times more MC events than the number of expected backgrounds

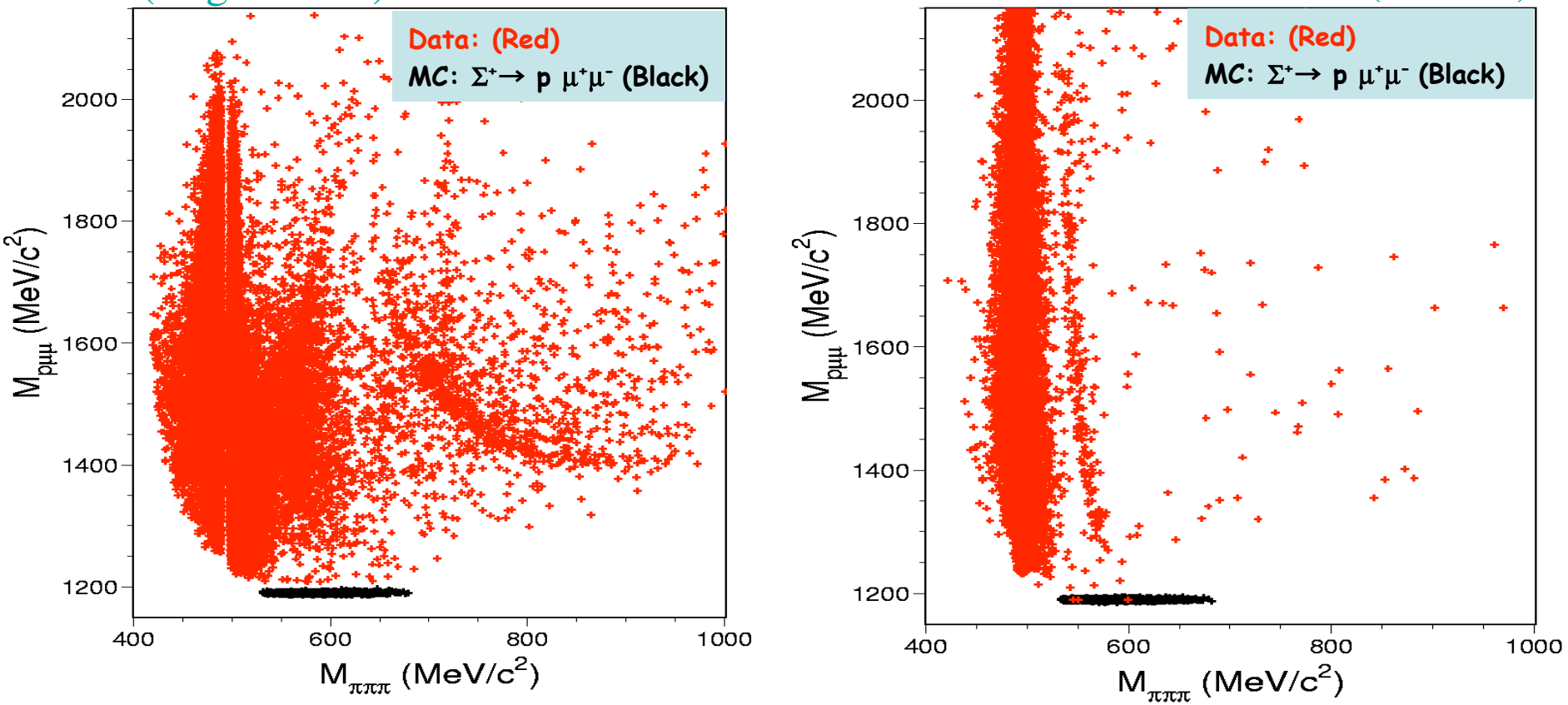
- Non-gaussian tails of K^+ decays, unknown and accidental background:

  Check with real data



Background Study: K^+ Decays (II)

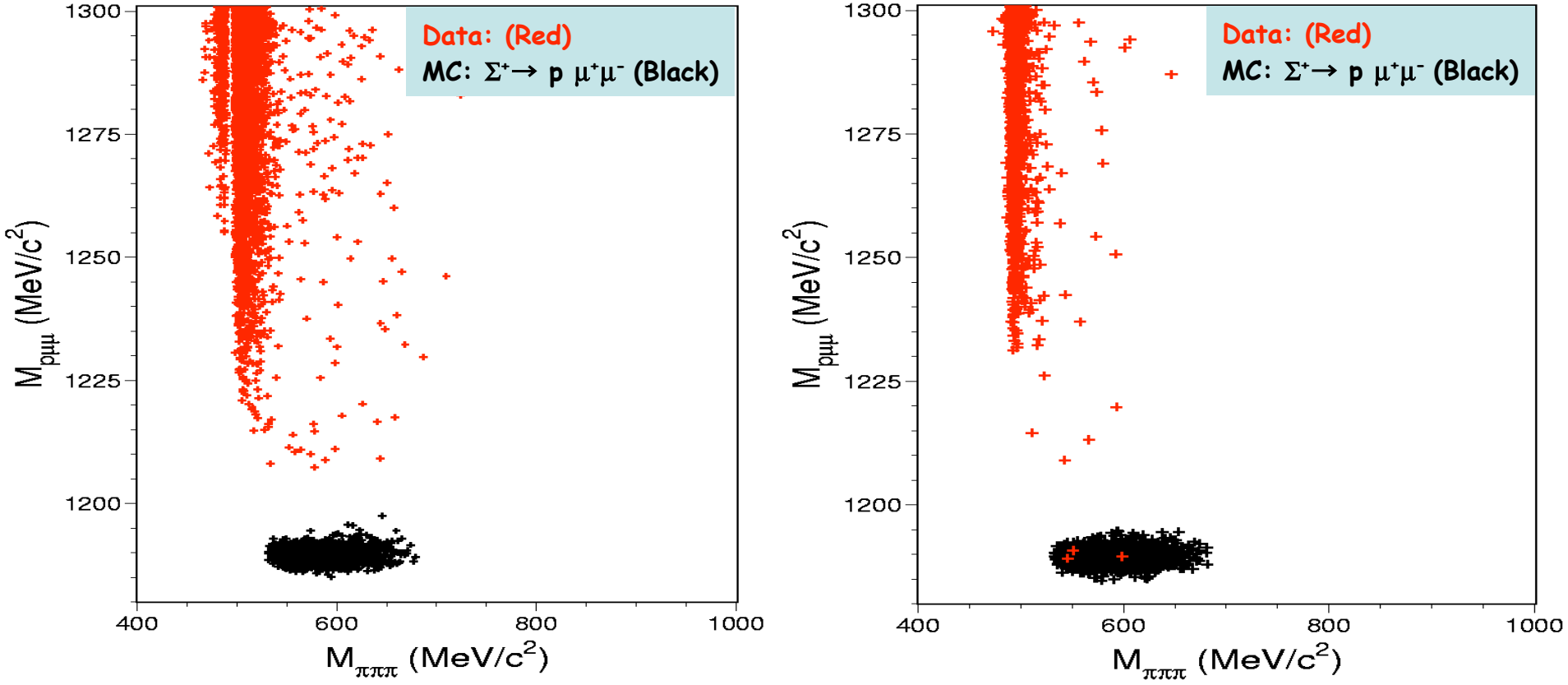
(single muon) Basic Selection Cut (dimuon)



- Use the single-muon sample: 30 times larger than the dimuon sample
- In the exclusive single-muon sample:
  more background, no events below 1200 MeV/c^2

Background Study: K^+ Decays (II)

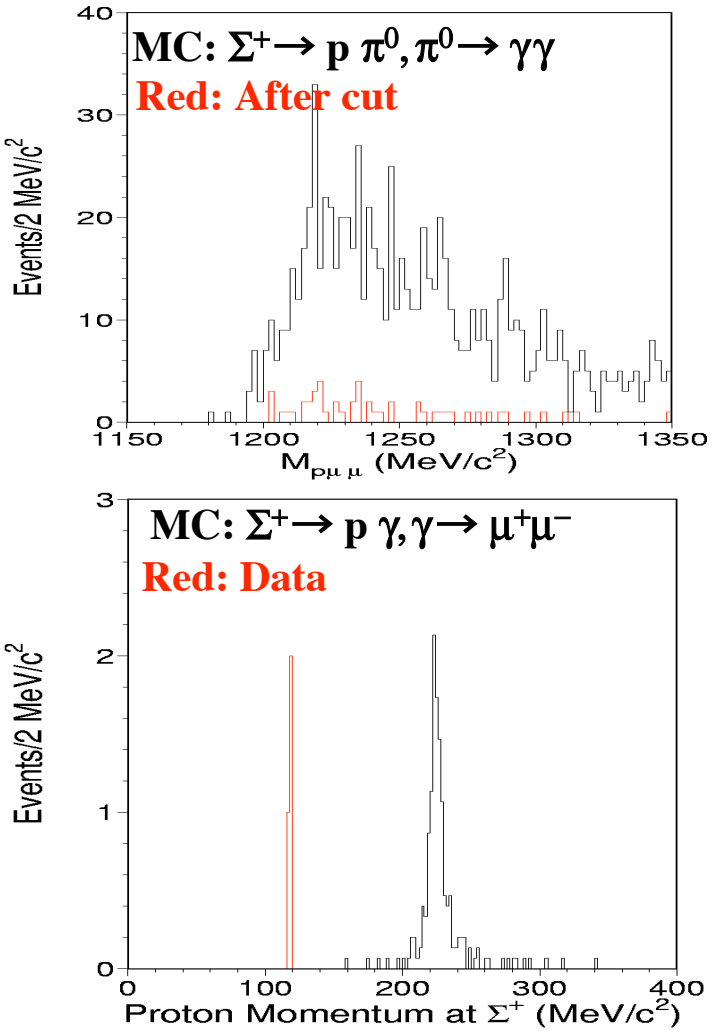
(single muon) Basic Selection Cut (dimuon)



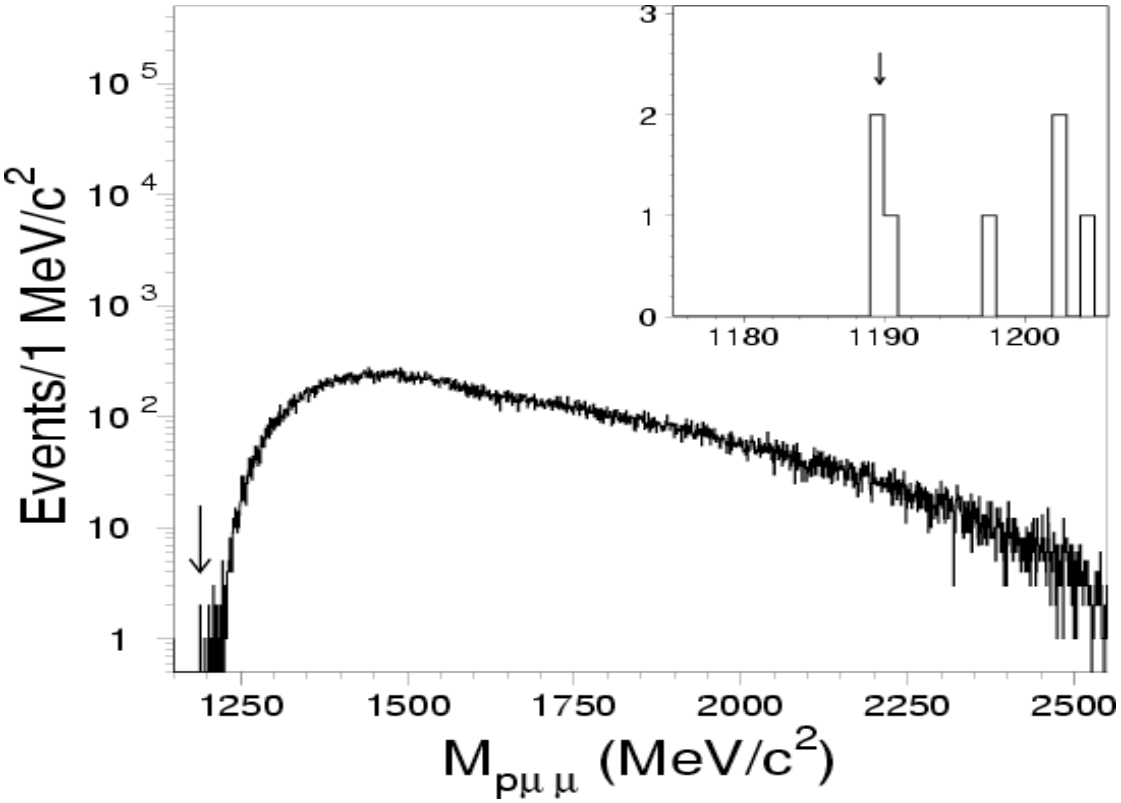
- Use the single-muon sample: 30 times larger than the dimuon sample
- In the exclusive single-muon sample:
  more background, no events below 1200 MeV/c^2

Background Study: Photon Conversion (III)

- The probability for **γ conversion to $\mu^+\mu^-$** at the window of the decay pipe: ~10^{-7}
- Photon sources from known decays:
  $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^+\gamma\gamma$
  $\Sigma^+ \to p\,\pi^0$, $\Sigma^+ \to p\,\gamma$
- Dimuon Trigger acceptance for photon conversions:
  ~10^{-2} to 10^{-4} (~10^{-3} for signal)
- Used 100~1000 times more MC events than the expected background level
- Checked proton momentum at the rest frame of Σ^+ **for 3 candidate events**

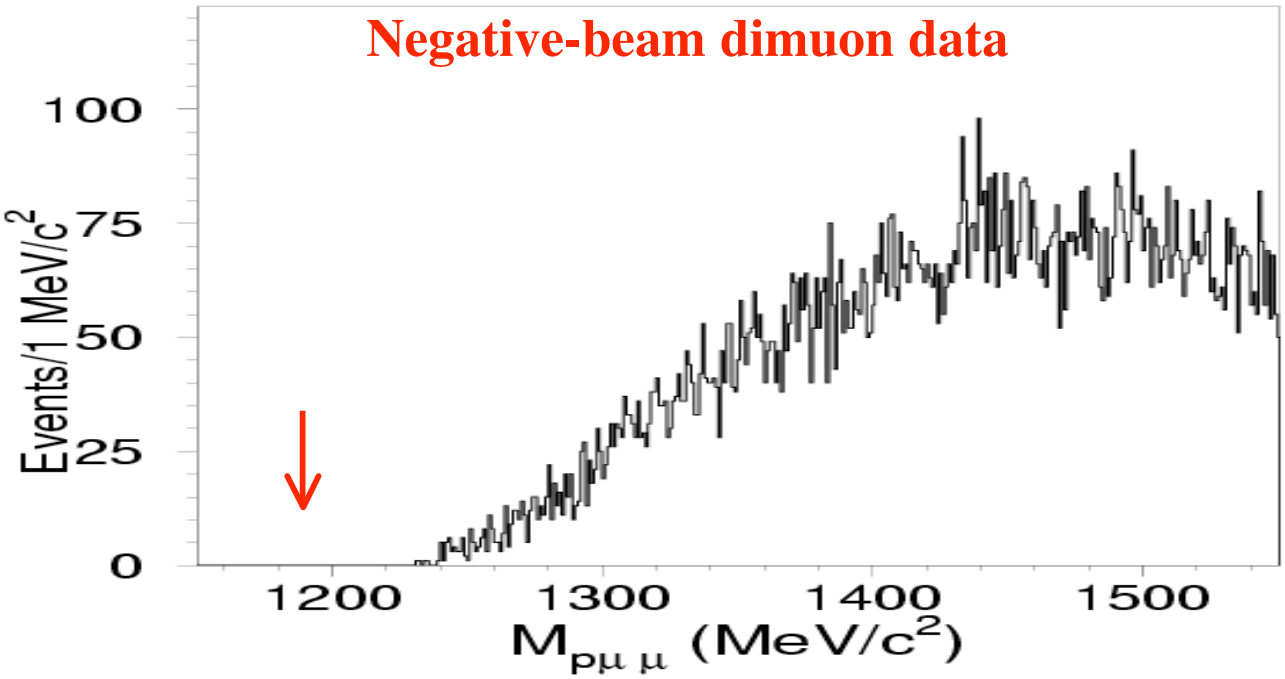


Background Study: Dimuon Sample (IV)



- Relaxed all basic selection cut values by 1σ of each cut resolution for the dimuon sample for positive beam:
  Increased background level but still no events within 8 σ.

Background Study: Dimuon Sample (V)



- No signal events in dimuon sample for negative beam:
  $\overline{\Sigma}^-$ production is suppressed by ~10 for negative beam.
  The dimuon sample with negative beam is 50% of positive beam.

Based on the background study,
the candidates are unlikely due to background.

Measuring $B(\Sigma^+ \to p\mu^+\mu^-)$

- Use $\Sigma^+ \to p\,\pi^0$, $\pi^0 \to e^+ e^- \gamma$ decays for normalization.
  (No gamma detector in HypreCP)

- Measure $B(\Sigma^+ \to p\mu^+\mu^-)$ according to the equation:

$$B(\Sigma^+ \to p\mu^+\mu^-) = \frac{N_{sig}^{obs}}{100 \cdot N_{nor}^{obs}} \frac{A_{nor}}{A_{sig}} \frac{\epsilon_{nor}}{\epsilon_{sig}} \frac{B(\Sigma^+ \to p\pi^0) \cdot B(\pi^0 \to ee\gamma)}{\epsilon_{\mu^+\mu^-} \cdot \epsilon_{rel}^{trig}}$$

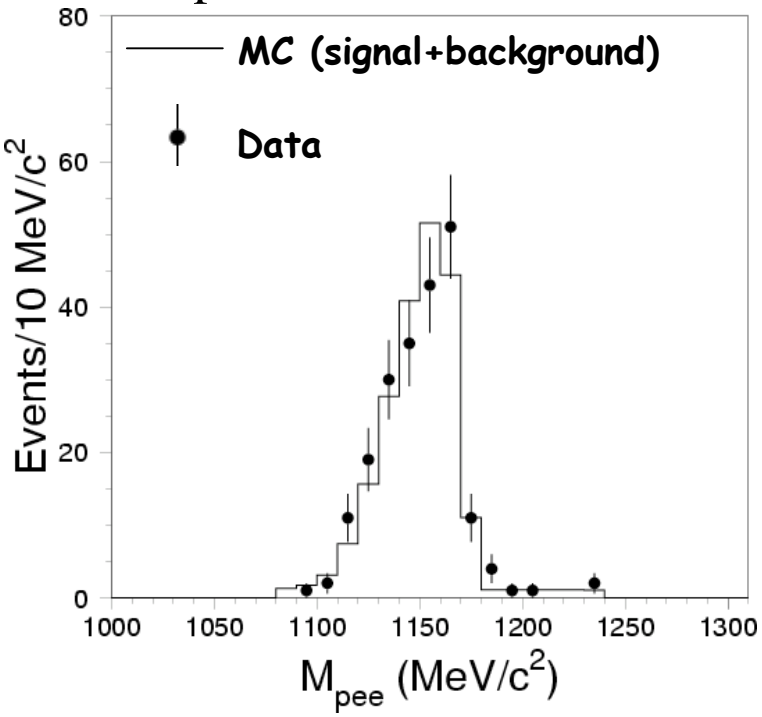
100	=	Prescale factor for normalization
N^{obs}	=	Number of observed events
A	=	Geometric acceptance
ϵ	=	Event selection efficiency
$\epsilon_{\mu^+\mu^-}$	=	Efficiency of identifying $\mu^+\mu^-$ **(96.2%)**
ϵ_{rel}^{trig}	=	Relative trigger efficiency **(91.9%)**

Mode	A_i (%)	ϵ_i (%)
$\Sigma^+ \to p\mu^+\mu^-$ (uniform decay)	0.17	71.0
$\Sigma^+ \to p\mu^+\mu^-$ (form factor)	0.26	71.2
$\Sigma^+ \to p\pi^0, \pi^0 \to e^+e^-\gamma$	0.26	5.6

Signal mode: unlike-sign dimuon trigger
Normalization mode: Left-Right trigger

Number of $\Sigma^+ \rightarrow p\,\pi^0$, $\pi^0 \rightarrow e^+ e^- \gamma$ Decays

- Apply the basic selection and f_{had} cuts to the data sample from the Left-Right trigger.
  (The cut values were optimized for the selection of **$\Sigma^+ \rightarrow p\,\pi^0$, $\pi^0 \rightarrow e^+ e^- \gamma$**)

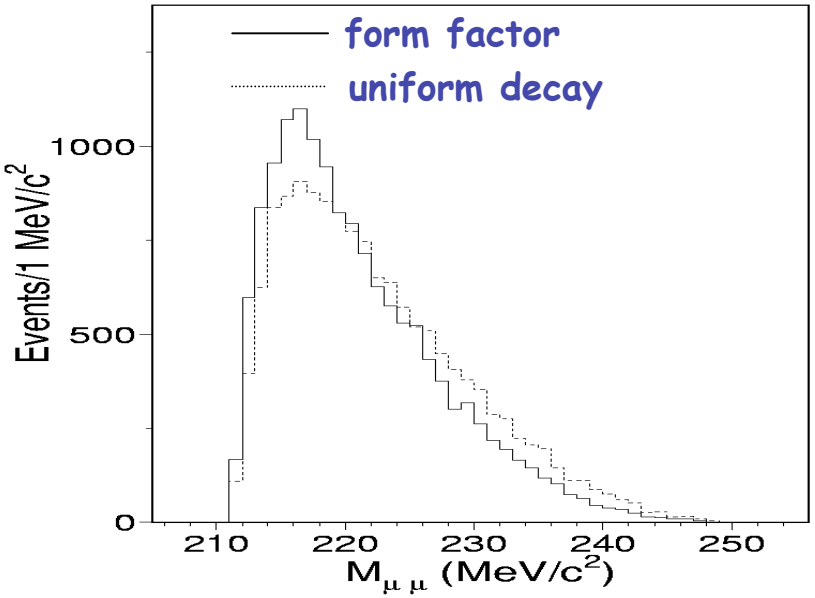


- Compared M_{pee} distribution for the data with MC signal and background events: **N_{norm}=(189.7 ± 27.4)**

- No. of Σ^+ decays in '99 positive data: **(2.14 ±0.31) x 10^{10}**

Interpretations of Results: $\Sigma^+ \to p\mu^+\mu^-$ (I)

- Use two decay models for $\Sigma^+ \to p\mu^+\mu^-$:



- If 3 candidates are $\Sigma^+ \to p\mu^+\mu^-$ decays,

$$B(\Sigma^+ \to p\mu^+\mu^-) = [1.3^{+1.0}_{-0.8} \pm 0.7] \times 10^{-7} \text{ (uniform decay)}$$

$$B(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8} \text{ (form factor)}$$

- If they are background,

$$B(\Sigma^+ \to p\mu^+\mu^-) < 5.2 \times 10^{-7} \text{ (uniform decay), @ 90\% C.L.}$$

$$B(\Sigma^+ \to p\mu^+\mu^-) < 3.4 \times 10^{-7} \text{ (form factor), @ 90\% C.L.}$$

Interpretations of Results: $\Sigma^+ \to p\mu^+\mu^-$ (II)

- In this measurement, we assume that the form-factor model is correct.
  - Choose the form factors to make $B(\Sigma^+ \to p\, e^+ e^-)$ as small as possible.

$\to$ $B(\Sigma^+ \to p\, e^+ e^-) = 8.9 \times 10^{-6}$.

$$B(\Sigma^+ \to p\mu^+\mu^-) = [1.1 \pm 0.3] \times 10^{-8} \quad \text{(form-factor model)}$$

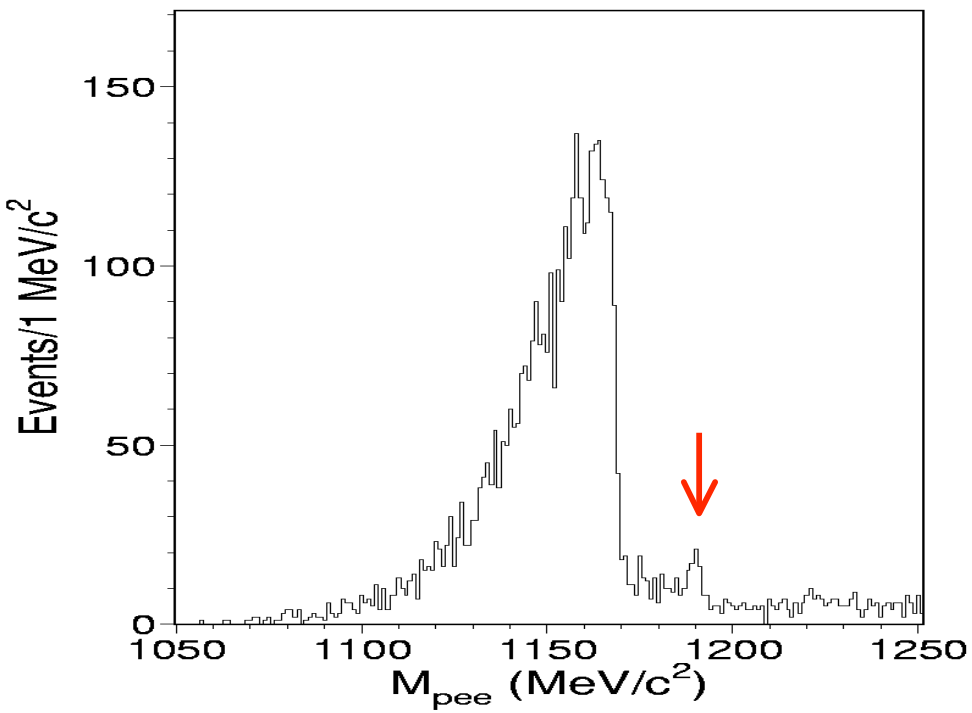
$$B(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.0] \times 10^{-8} \quad \textbf{(HyperCP)}$$

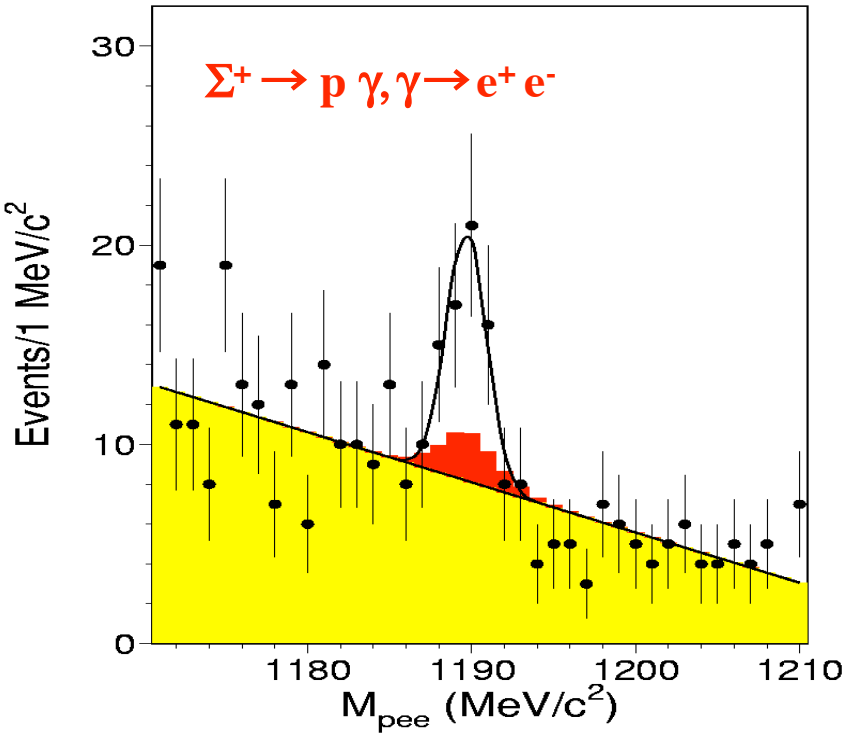
- If $B(\Sigma^+ \to p\, e^+ e^-) < 7 \times 10^{-6}$ in PDG is correct, we would expect $B(\Sigma^+ \to p\mu^+\mu^-) \sim 10^{-9}$.

- The R-value would give an idea to check the form-factor model.

$$R = \frac{B(\Sigma^+ \to pe^+e^-)}{B(\Sigma^+ \to p\mu^+\mu^-)}$$

Search for $\Sigma^+ \rightarrow p\, e^+ e^-$ Decays

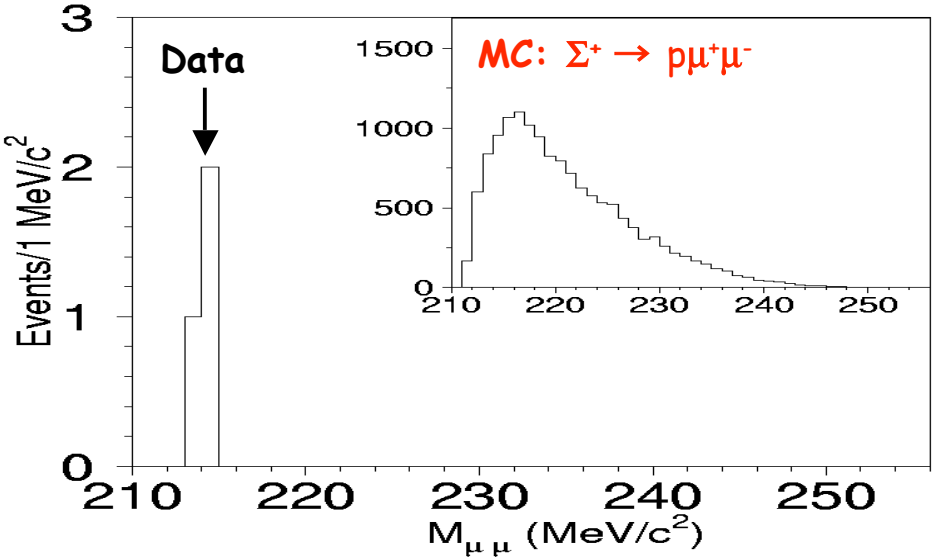


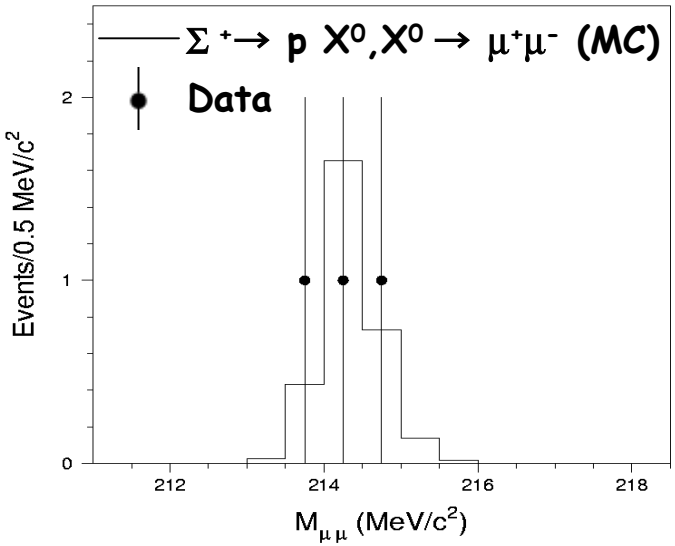


- Observed the peak at Σ^+ with the hypothesis, $\Sigma^+ \rightarrow p\, e^+ e^-$ decays.
- In very preliminary study with the prescaled data set and MC study of $\Sigma^+ \rightarrow p\, \gamma, \gamma \rightarrow e^+ e^-$, the observed peak is consistent with $\Sigma^+ \rightarrow p\, e^+ e^-$ decays.

Interpretations of Results: $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$

- Dimuon masses for 3 candidates are clustered within ~ 1 MeV/c^2.





- Probability for dimuon masses of 3 events to be within 1 MeV for $\Sigma^+ \to p\mu^+\mu^-$ decays in SM (form factor) is 0.8%.
- Suggests two-body decays, $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$:

$$M_{X^0} = (214.3 \pm 0.5)\ \mathrm{MeV}/c^2$$

$$B(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9} \pm 1.5] \times 10^{-8}$$

Systematics for Each Scenario

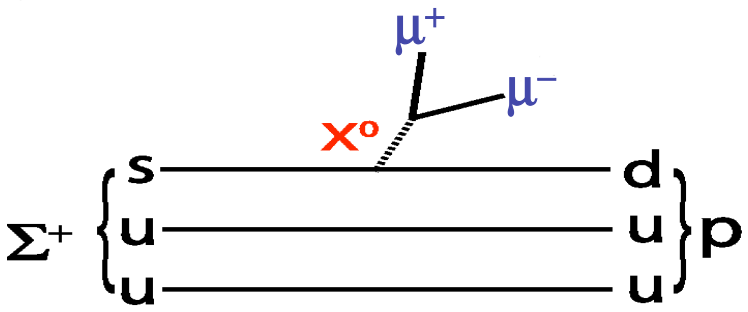
	$\Sigma^+ \to p\mu^+\mu^-$	$\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-$
	unform phase space (form factor)	
Source	σ_B/B (%)	σ_B/B (%)
Normalization	14.7 (14.7)	14.7
Modeling of Σ^+ production	52.1 (54.3)	44.6
Beam targeting	11.5 (11.1)	8.7
Magnetic field	3.8 (2.2)	3.9
Trigger efficiency	1.5 (1.5)	1.5
Muon identification	0.3 (0.3)	0.3
$\Sigma^+ \to p\mu^+\mu^-$ decay model	(28.9)	
π^0 form factor	1.8 (1.8)	1.8
$B(\Sigma^+ \to p\pi^0)$	0.6 (0.6)	0.6
$B(\pi^0 \to e^+e^-\gamma)$	2.7 (2.7)	2.7
MC statistics	1.3 (1.3)	1.3
Total	55.6 (64.4)	48.1

- Main source of systematic error: modeling of Σ^+ momentum spectrum.
- Total systematic error is comparable to the statistical error.

Speculations for $\Sigma^+ \rightarrow pX^0$, $X^0 \rightarrow \mu^+\mu^-$ Scenario

- Before taking the $\Sigma^+ \rightarrow pX^0$, $X^0 \rightarrow \mu^+\mu^-$ seriously, we have to consider the following questions:
  - Is the X^0 a **hadron** ?
  - Is the X^0 **a scalar (pseudoscalar) or a vector (axial vector) particle** ?
  - Is there a **theoretical model** that suggests an X^0 (214.3 MeV/c^2) ?
  - **Why previous experiments have not seen the X^0 ?**
  - Other possible **decay modes** ?

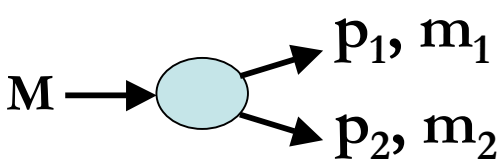
- In this discussion, we assume that the X^0 is short-lived ($c\tau$ < ~mm), and is produced by this diagram:



Is the X^0 a hadron ?

The X^0 can not be a hadron.

- For two-body decays, the partial decay rate is given by



$$d\Gamma \sim |\mathcal{M}|^2 |p_1| d\Omega$$

matrix element

- Suppose that the matrix element for $\Sigma^+ \to p\,\pi^0$ is similar to $\Sigma^+ \to pX^0$.

$$\frac{B(\Sigma^+ \to pX^0)}{B(\Sigma^+ \to p\pi^0)} \approx 0.6 \longrightarrow B(\Sigma^+ \to pX^0) \approx 30\%$$

Note that $B(\Sigma^+ \to p\pi^0) + B(\Sigma^+ \to n\pi^+) \approx 100\%$

Previous experiments should have observed the X^0 if it were a hadron.

Is the X^0 a scalar or a vector particle ?

Either a scalar or a vector particle is possible at current level of statistics.

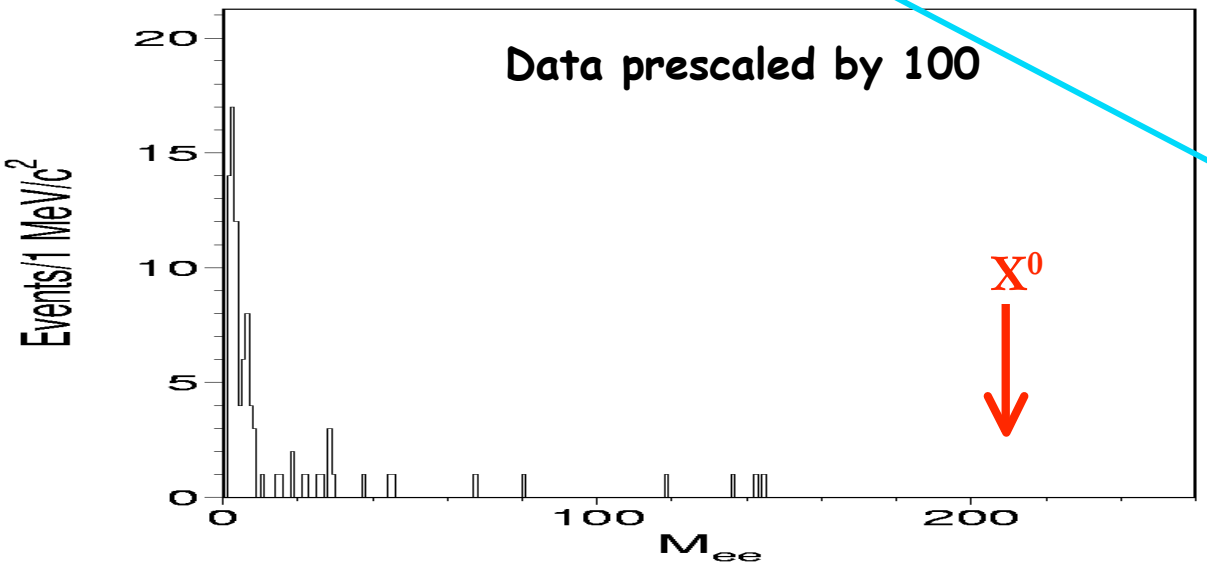
- If the X^0 is a vector particle, we expect

$$\frac{B(X^0 \to e^+e^-)}{B(X^0 \to \mu^+\mu^-)} \approx 2.0 \quad \Rightarrow \quad B(\Sigma^+ \to pX^0, X^0 \to e^+e^-) \approx 6.2 \times 10^{-8}$$

- If the X^0 is a scalar particle, $X^0 \to e^+e^-$ is a helicity suppressed mode.

$$\frac{B(X^0 \to e^+e^-)}{B(X^0 \to \mu^+\mu^-)} \approx 10^{-4}\left(= m_e^2/m_\mu^2\right) \quad \Rightarrow \quad B(\Sigma^+ \to pX^0, X^0 \to e^+e^-) \approx 10^{-12}$$

- Check the dieletron masses for the observed $\Sigma^+ \to pe^+e^-$ decays.



0.2 e^+e^- events

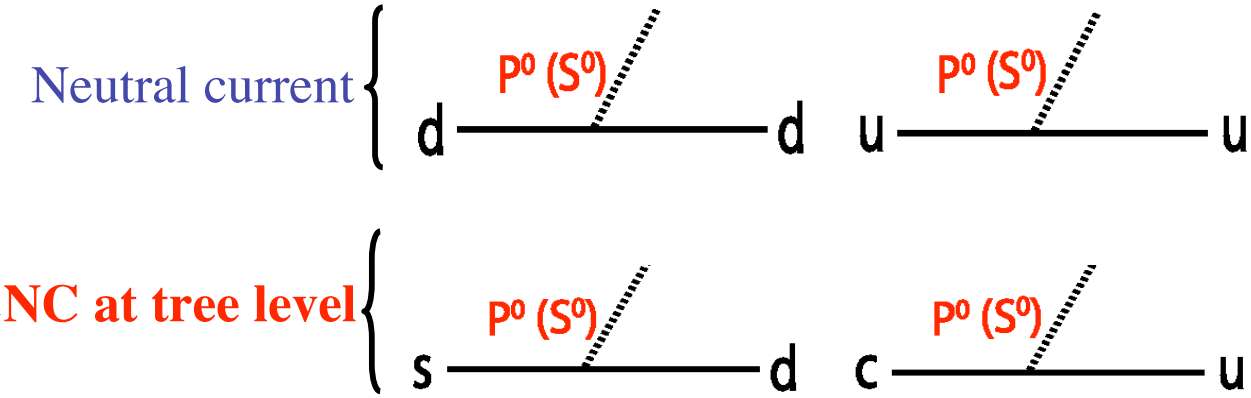
0 e^+e^- events

Is there a theoretical model that suggests an X^0 (214.3 MeV/c^2) ? (I)

- In SUSY, spontaneous SUSY breaking generates Goldstone fermion (Goldstino), which gives the longitudinal component of gravitino.
  There should exist superpartners of Goldstino:
  sgoldstinos, pseudoscalar P^0 and scalar S^0
  The masses of P^0 and S^0 are generally arbitrary.
  → **Perhaps < a few GeV or a few MeV**

- P^0 and S^0 can couple with SM particles, quarks, leptons and gauge bosons.

- Interactions of sgoldstinos P^0 and S^0 with quarks are given by



Is there a theoretical model that suggests an X^0 (214.3 MeV/c^2) ? (II)

The observed events are a possible candidate for sgoldstino in SUSY.

- If the masses of P^0 and S^0 are less than two pion masses, they can decay into photon or lepton pairs (D.S. Gorbunov, Nucl. Phys. B602 (2001) 213).

$$\Gamma(P^0(S^0) \to \gamma\gamma) = \frac{m^3_{s^0(p^0)} M_{\gamma\gamma}}{32\pi F^2}, \qquad \Gamma(P^0 \to l^+l^-) = \frac{m^3_{p^0} A_l^2}{16\pi F^2} \frac{m_l^2}{m_{p^0}^2} (1 - \frac{4m_l^2}{m_p^2})^{1/2}$$

F : SUSY breaking scale $\sqrt{F} \geq 217$ GeV by CDF, PRL 85, 1378 (2000)
$M_{\gamma\gamma}$: order of photino mass (~100 GeV)
A_l : soft mass term (~100 GeV)

$M_{P^0} = 214.3$ MeV/c^2 $\sqrt{F} = 1$ TeV	$M_{\gamma\gamma} = 100$ GeV $A_l = 100$ GeV	$M_{\gamma\gamma} = 100$ GeV $A_l = 1000$ GeV	$M_{\gamma\gamma} = 1000$ GeV $A_l = 100$ GeV
$B(P^0 \to \gamma\gamma)$	91.3%	9.5 %	99.9 %
$B(P^0 \to \mu^+\mu^-)$	8.7 %	90.5 %	0.1 %
$B(P^0 \to e^+e^-)$	10^{-3} %	0.01 %	10^{-5} %
$c\tau$ (cm)	0.02	0.002	0.0002

short lived one (=consistent with single vertex for the observed events)

Why previous experiments have not seen X^0 ? (I)

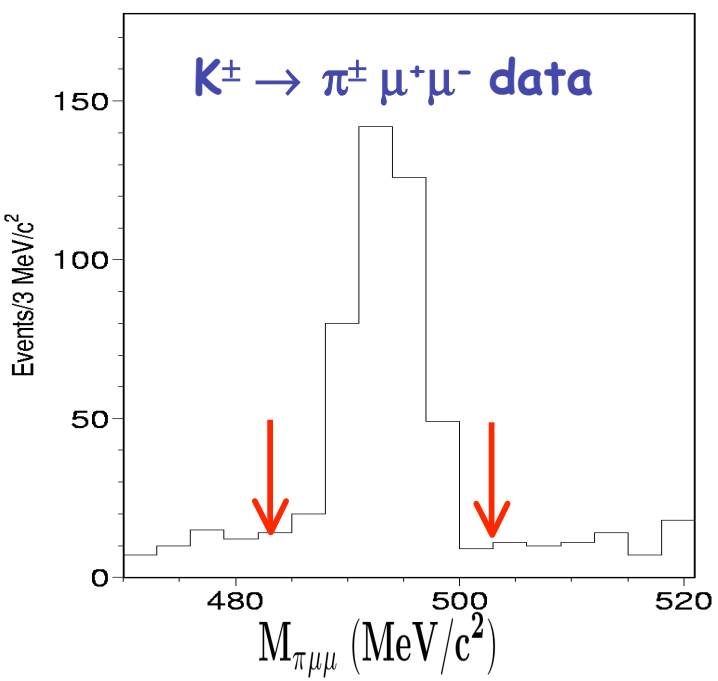
- Many experiments have searched for a light boson:

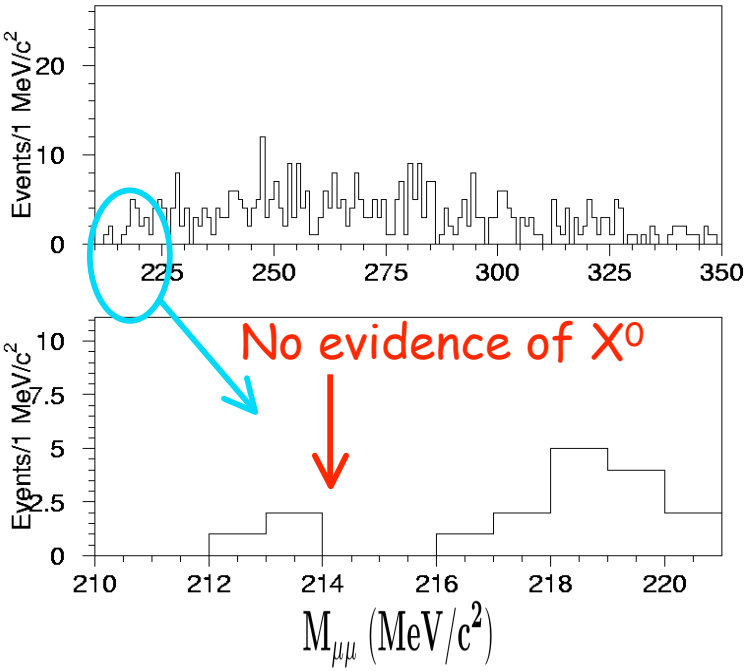
Mode	Upper Limits	Assumption L=long lived, S=short lived
$K^+ \to \pi^+ X^0$	$< 4.5 \times 10^{-8}$ *to* 10^{-11}	$0 MeV < m_{X^0} < 300$ MeV (L)
$K^+ \to \pi^+ X^0, X^0 \to \gamma\gamma$	$< 5.0 \times 10^{-8}$	0 MeV $< m_{X^0} < 100$ MeV (S)
$K^+ \to \pi^+ X^0, X^0 \to \mu^+\mu^-$	$< 1.5 \times 10^{-7}$	220 MeV $< m_{X^0} < 300$ MeV (S)
$K^+ \to \pi^+ X^0$	$< 2 \times 10^{-5}$	5 MeV $< m_{X^0} < 300$ MeV (L & S)
$\eta \to \gamma X^0$	$< 6 \times 10^{-5}$	200 MeV $< m_{X^0} < 525$ MeV (L)
$\Upsilon \to \gamma X^0$	$< 1.3 \times 10^{-5}$	$m_{X^0} < 5$ GeV (L)
$\Upsilon \to \gamma X^0 X^0$	$< 1 \times 10^{-3}$	$m_{X^0} < 3.1$ GeV (L)

A short lived X^0 of mass 214.3 MeV/c^2 has not been well searched for.

Why previous experiments have not seen X^0 ? (II)

- Search for the decay $K^+ \to \pi^+ X^0$, $X^0 \to \mu^+\mu^-$ using HyperCP data.





Note: 1 event sensitivity is an **order of 10^{-10}**.

Larger phase space for $K^+ \to \pi^+ X^0$ than for $\Sigma^+ \to p X^0$.

Either X^0 is a vector particle or
we need a mechanism for $K^+ \not\to \pi^+ X^0$.

Why previous experiments have not seen X^0 ? (III)

- The vector particle possibility can be ruled out by $\mathbf{K_L} \to \gamma\mu^+\mu^-$:

KTeV collected 9327 events, $B(K_L \to \gamma\mu^+\mu^-) = (3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$

No evidence for $\mathbf{K_L} \to \gamma \mathbf{X^o}, \mathbf{X^o} \to \mu^+\mu^-$

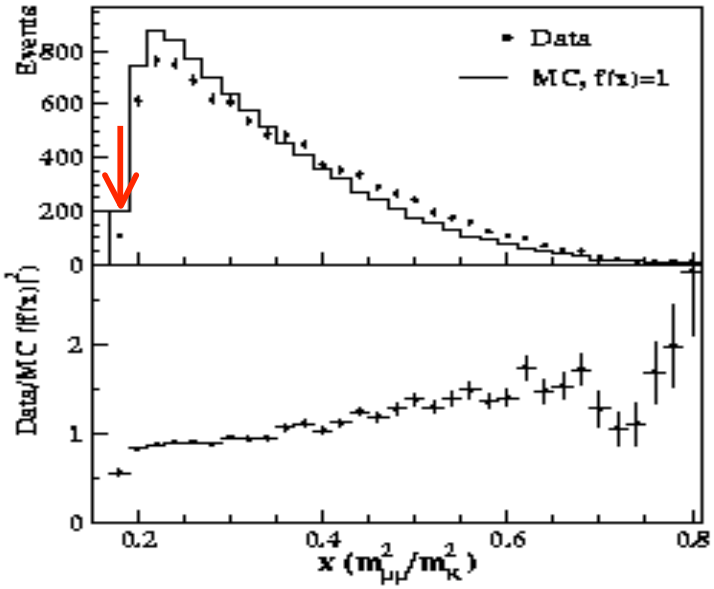


FIG. 3. The dimuon mass distributions for data and for Monte Carlo with no form factor (top). The data/Monte Carlo ratio is a direct measurement of the form factor (bottom). The Monte Carlo is normalized to the total number of data events.

Why previous experiments have not seen the X^0 ? (IV)

- There is a possibility for **parity-conserving sgoldstino interaction.**
  (D. S. Gorbunov and V. A. Rubakov, PRD 64, 054008 (2001))

  "Parity conservation in sgoldstino interactions with quarks and gluons may not be accidental… It is likely that sgoldstino interaction will conserve parity in supersymmetric versions of other models designed to solve the strong CP problem without introducing light axion."

	K^+	$\longrightarrow$	π^+	X^0
Parity:	-1		-1	−1

If X^0 is a pseudoscalar, this is suppressed (parity violation).

	K^+	$\longrightarrow$	π^+	π^0	X^0
Parity:	-1		-1	-1	-1

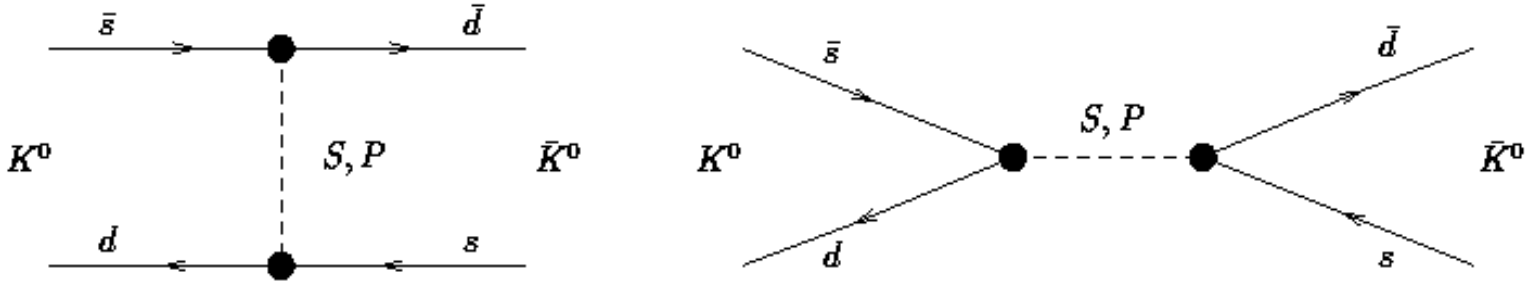
If X^0 is a pseudoscalar, this is allowed (parity conservation).

$B(K^+ \to \pi^+\pi^0 X^0) = 1.5 \times 10^{-6}$ to 4×10^{-4} $(m_{X^0} < 200\ \mathrm{MeV})$ (hep-ex/0308061)

Perhaps the X^0 is a candidate for pseudoscalar sgoldstino (P^0) with parity conserving interaction.

Why previous experiments have not seen X^0 ? (IV)

- Allowed limit for $\Sigma^+ \rightarrow pX^0$ with parity-conserving sgoldstino interaction. (private communication with D. S. Gorbunov)



Using Δm_K (K_L-K_S mass difference) and ε parameter of CP violation, extract the constraints on sgoldstino coupling in s→d quark transition.

$B(\Sigma^+ \rightarrow pX^0) < 10^{-3}$ to 10^{-6} depending on the constraints.

Other possible decay modes ?

- Possible decay modes to search for **pseudoscalar X^0 (214.3 MeV/c^2) with parity-conserving interaction:**

Mode	Q value (MeV)
$K^+ \to \pi^+\pi^0 X^0$	5.0
$K_{L,S} \to \pi^+\pi^- X^0$	4.3
$K_{L,S} \to \pi^0\pi^0 X^0$	13.5
$\phi(1020) \to K^+\pi^- X^0$	386.2
$\Sigma^+ \to p X^0$	36.8
$\Omega^- \to \Xi^- X^0$	136.9

} $\mathbf{X^0 \to \gamma\gamma, \mu^+\mu^-}$

Note: No measurements for $\mathbf{K_{L,S} \to \pi\pi\gamma\gamma, \pi\pi\mu^+\mu^-}$

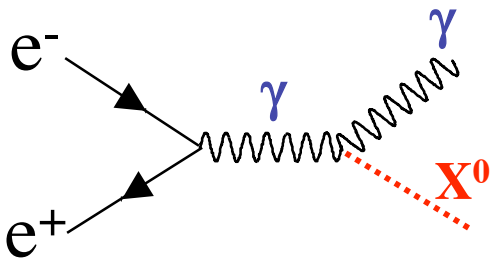
– Decay modes for charm and beauty mesons:

$D^+ \to \pi^+\pi^0 X^0$
$B^+ \to K^+\pi^0 X^0$

} more phase space than s-quark sector

Other Possible Searches

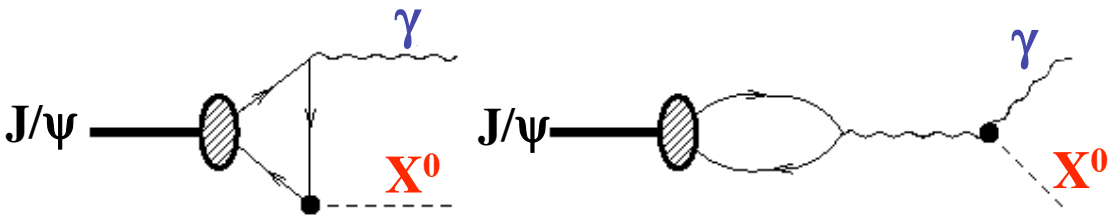
- $e^+ e^- \rightarrow \gamma X^0$



$\sigma(e^+ e^- \rightarrow \gamma X^0) \sim 0.01$ pb to 1 fb @ $\sqrt{s} = 10$ GeV

- $J/\psi \rightarrow \gamma X^0$

  (CLEO-c will collect ≈1 billion of J/ψ)



$B(J/\psi \rightarrow \gamma X^0) \sim 10^{-8}$

Summary

- We observed three candidates with p $\mu^+\mu^-$ mass consistent with Σ^+ decays: No background within 20 σ
- This is the rarest decay ever observed in the baryon sector.

$$B(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8}$$ (form factor)

- The dimuon masses for three candidates are clustered within ~ 1 MeV/c^2, which could imply $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$:

$$M_{X^0} = (214.3 \pm 0.5)\ \mathrm{MeV}/c^2$$

$$B(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = [3.1^{+2.4}_{-1.9} \pm 1.5] \times 10^{-8}$$

The X^0 would be a candidate for pseudoscalar sgoldstino with parity-conserving interaction in SUSY.

- Further work is needed to confirm our result.

Once the X^0 is confirmed,
HyperCP will provide
wine and cheese to people here !

Backup Slides

Hadronic Matrix Element for $\Sigma^+ \to p\, l^+ l^-$

- The most general hadronic matrix element for this decay is given by

$$\Gamma^\mu = (a_1 + a_2\gamma_5)\gamma^\mu + (b_1 + b_2\gamma_5)\frac{i}{2}\sigma^{\mu\nu}q^\nu + (c_1 + c_2\gamma_5)q^\mu$$

Form factors : $a_1,\ a_2,\ b_1,\ b_2,\ c_1,\ c_2.$ $\quad q^\mu : 4-$momentum for photon

$$a_1(q^2) \propto q^2 c_1(q^2), \quad a_2(q^2) \propto q^2 c_2(q^2)$$

⟶ **Need only 4 form factors**

- Form factors, b_1 and b_2, can be extracted by the decay rate and parameter for $\Sigma^+ \to p\gamma$:

$$\Gamma(\Sigma^+ \to p\gamma) \propto (|b_1|^2 + |b_2|^2), \quad \alpha(\Sigma^+ \to p\gamma) = \frac{2\mathrm{Re}(b_1 b_2^*)}{|b_1|^2 + |b_2|^2}$$

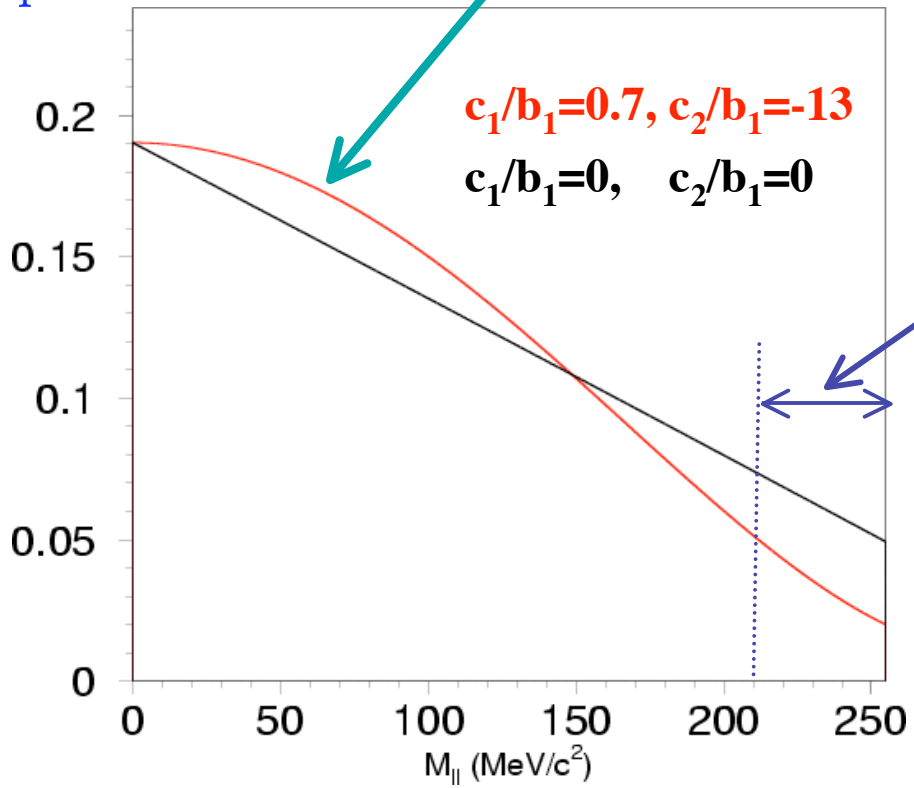
$$b_2(0)/b_1(0) = (-0.46 \pm 0.07), \quad |b_1(0)| = (6.8 \pm 0.2)\ \mathrm{MeV}$$

Form Factor Function

$$\frac{d\Gamma}{dx} = \frac{(x^2+2m_l^2)\lambda^{1/2}\sqrt{1-4m_l^2/x^2}}{x^3} \times (\text{form factor function})$$

$$\lambda = m_\Sigma^4 + m_p^4 + x^4 - 2m_\Sigma^2 m_p^2 - 2m_\Sigma^2 x^2 - 2m_p^2 x^2$$

x = dilepton mass



Muon channel

Interactions of sgoldstino with Quarks

- Interactions of sgoldstinos P^0 and S^0 with quarks are given by

$$\mathcal{L} = -P^0(h^D_{ij}\bar{d}_i\gamma^5 d_j + h^U_{ij}\bar{u}_i\gamma^5 u_j) - S^0(h^D_{ij}\bar{d}_i d_j + h^U_{ij}\bar{u}_i u_j)$$

$$d_i = (d, s, b), \quad u_i = (u, c, t)$$

Off-diagonal elements give FCNC:

$$\mathcal{L} = -P^0(h^D_{12}\bar{d}\gamma^5 s + h^U_{12}\bar{u}_i\gamma^5 c) - S^0(h^D_{12}\bar{d}s + h^U_{12}\bar{u}c) + \ldots$$

Why we observed an X^0 from Σ^+ Decays ?

- In $\Sigma^+ \rightarrow p\ \pi^0$ decays, the matrix element is given by

$$\mathcal{M} = \overline{\psi}_{\Sigma^+}(A + B\gamma^5)\psi_p,$$

A and B are parity-violating and -conserving amplitudes, respectively.
A=-3.27 and B=26.6 in 10^{-7} unit from the decay parameter for $\Sigma^+ \rightarrow p\ \pi^0$ decays.
The parity-conserving amplitude is an order of magnitude larger.

This might be a true that the parity-conserving amplitude is dominant for a pseudoscalar X^0 production.

Why previous experiments have not seen X^0 ? (IV)

- Allowed limit for $\Sigma^+ \to pX^0$ with parity-conserving sgoldstino interaction (private communication with D. S. Gorbunov)

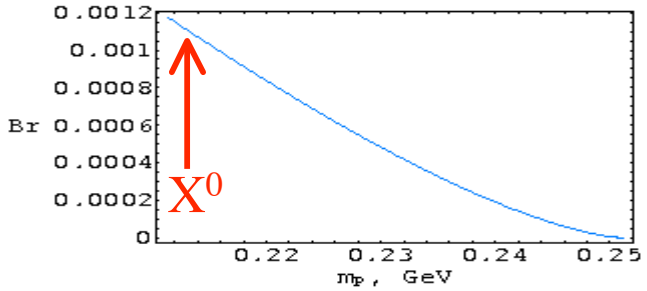


Figure 3: Upper bound on the branching ratio of hyperon decay into proton and light pseudoscalar sgoldstino for $2m_\mu < m_P < m_\Sigma - m_p$ in models with $\mathrm{Im}[h_{12}^{(D)}] \gg (\ll) \mathrm{Re}[h_{12}^{(D)}]$.

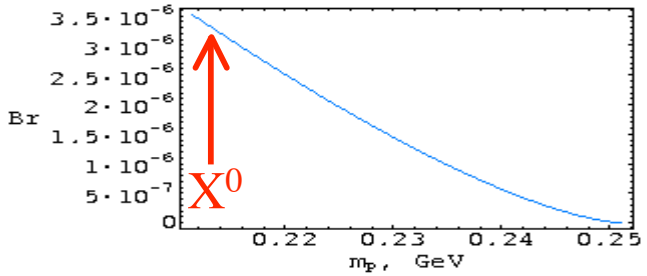


Figure 4: Upper bound on the branching ratio of hyperon decay into proton and light pseudoscalar sgoldstino for $2m_\mu < m_P < m_\Sigma - m_p$ in models with $\mathrm{Im}[h_{12}^{(D)}] \simeq \mathrm{Re}[h_{12}^{(D)}]$.

$B(\Sigma^+ \to pX^0) < 10^{-3}$ to 10^{-6} depending on the parameter.

Summary of the Basic Selection Cuts

- 3 tracks with unlike-sign dimuon trigger: **$\mu^+\mu^-$ proton**
- Decay vertex:

  100 cm < v_z < 1300 cm
- Single vertex tagging:

  χ^2/ndf < 1.5, DCA < 2.5 mm
- Target pointing:

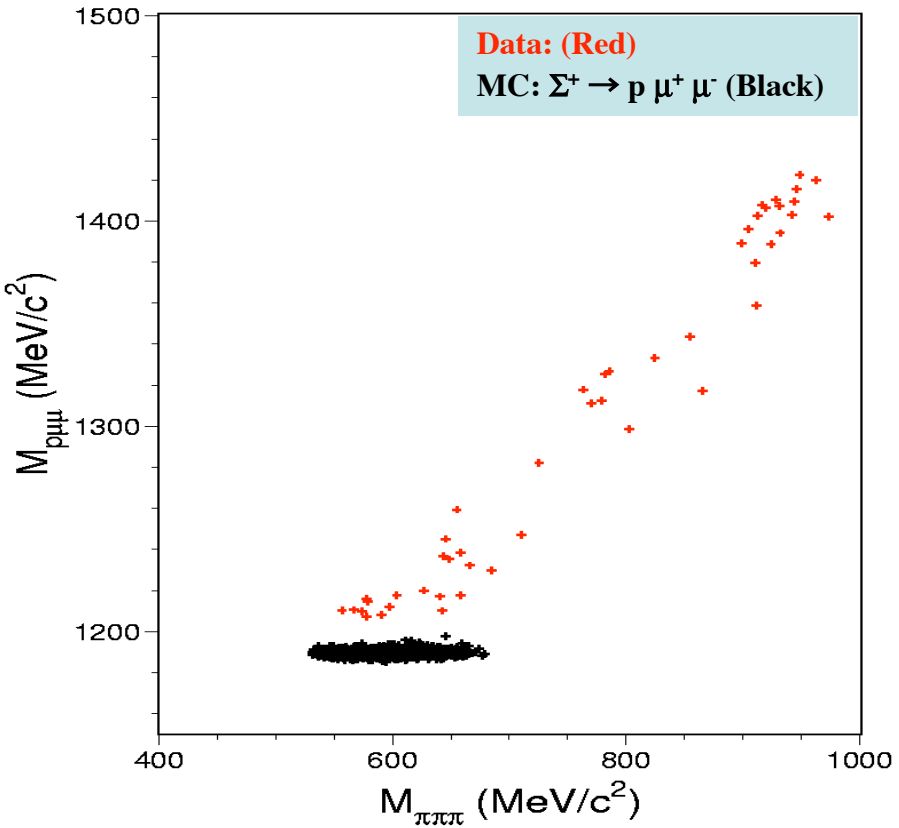
  R < 3.5 mm
- Total momentum:

  120 GeV < P_{tot} < 240 GeV

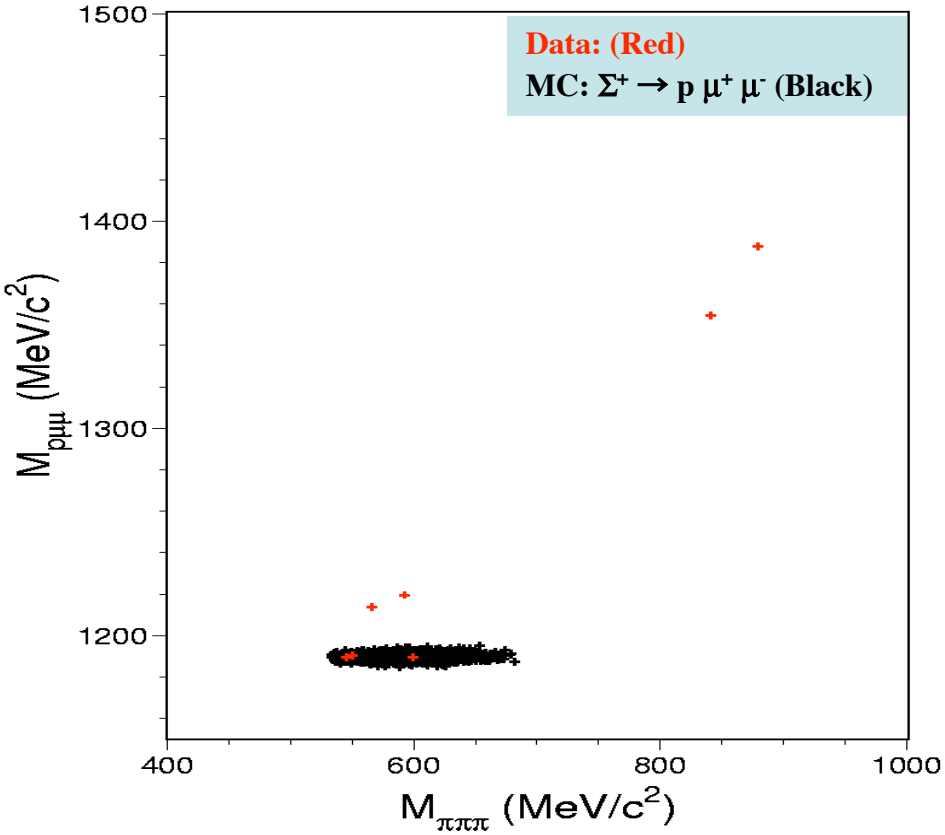
Background Study: Single Muon Sample

Basic Selection and f_{had} Cuts

(single muon)

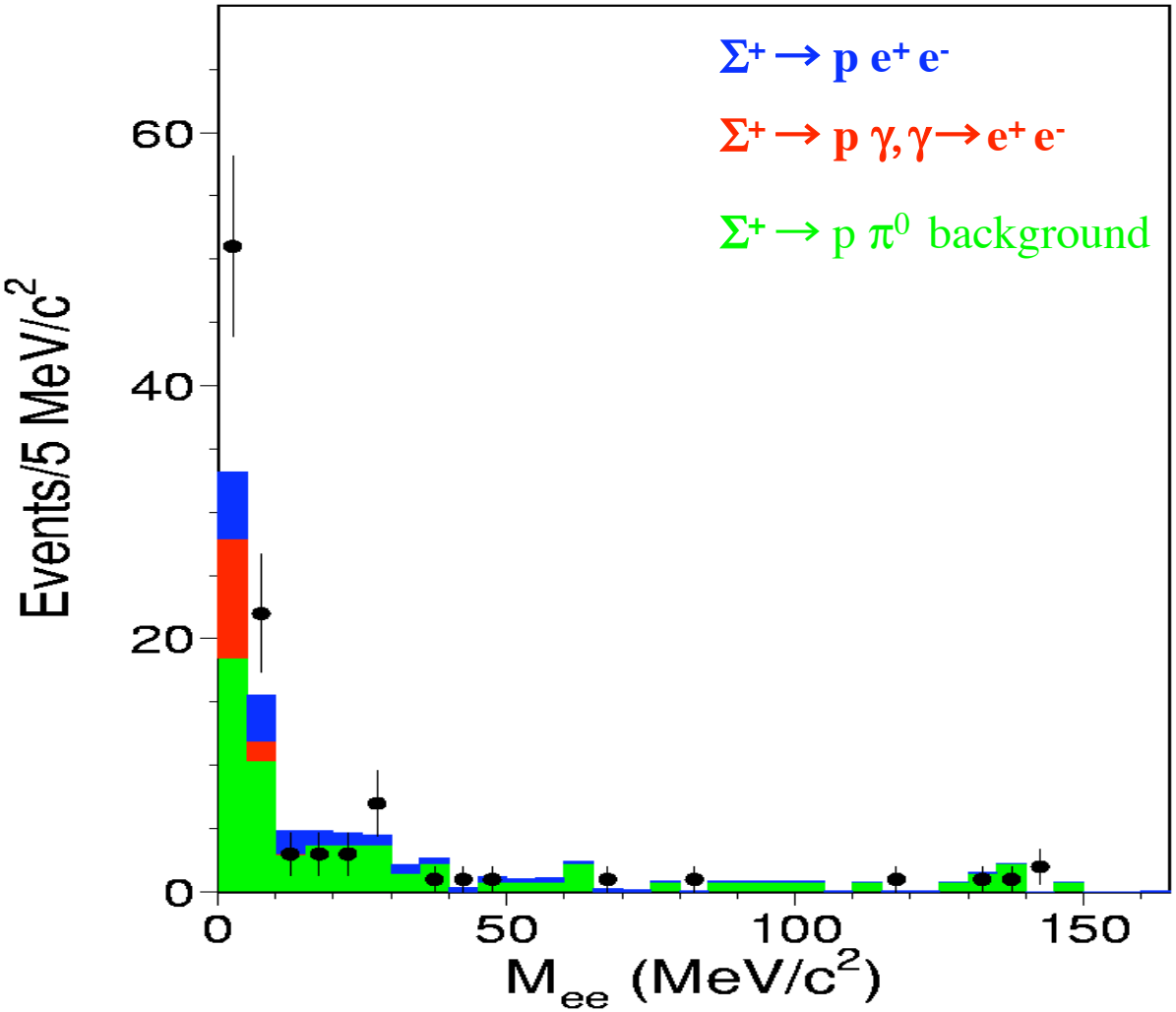


(dimuon)



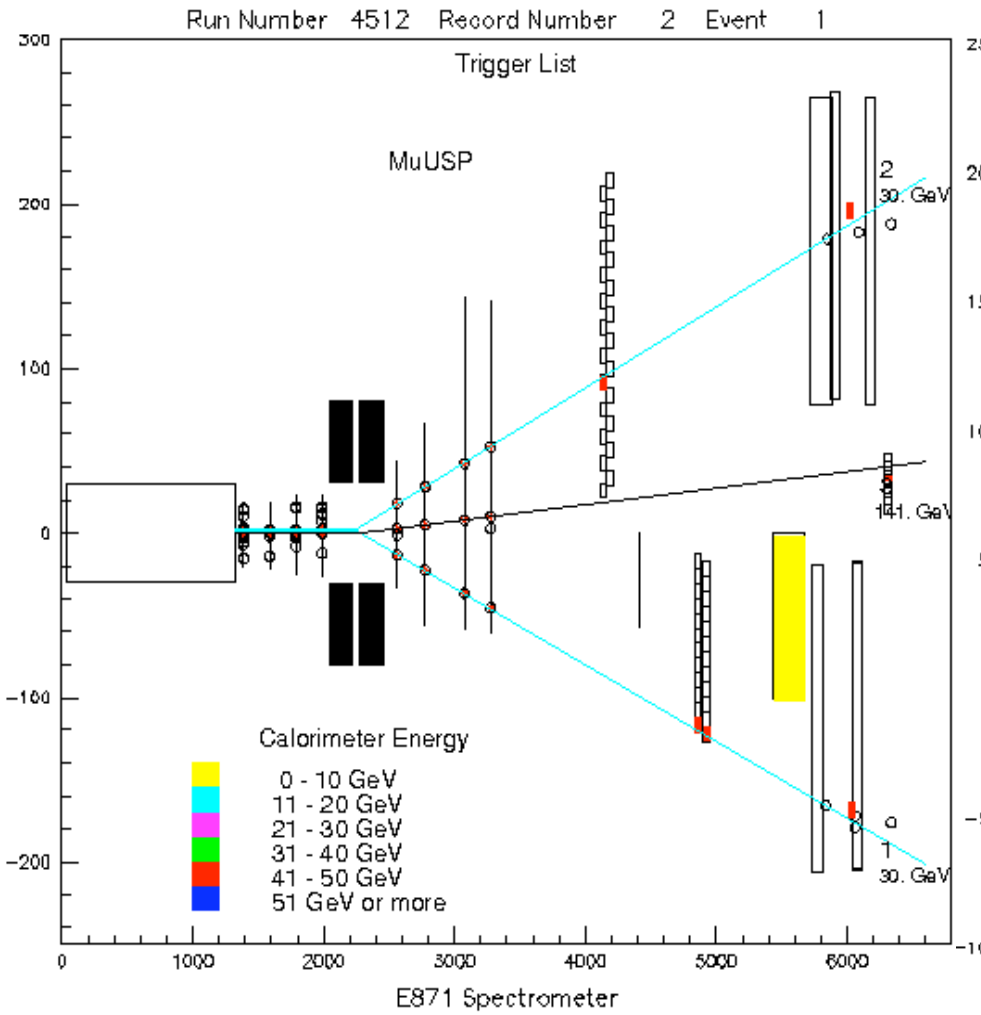
- Almost no K^+ decays in both samples.
- Background level above 1200 MeV/ c^2 in the dimuon sample:
  (3.6 ± 0.5) events estimated from the single muon sample
  4 events observed in the dimuon sample

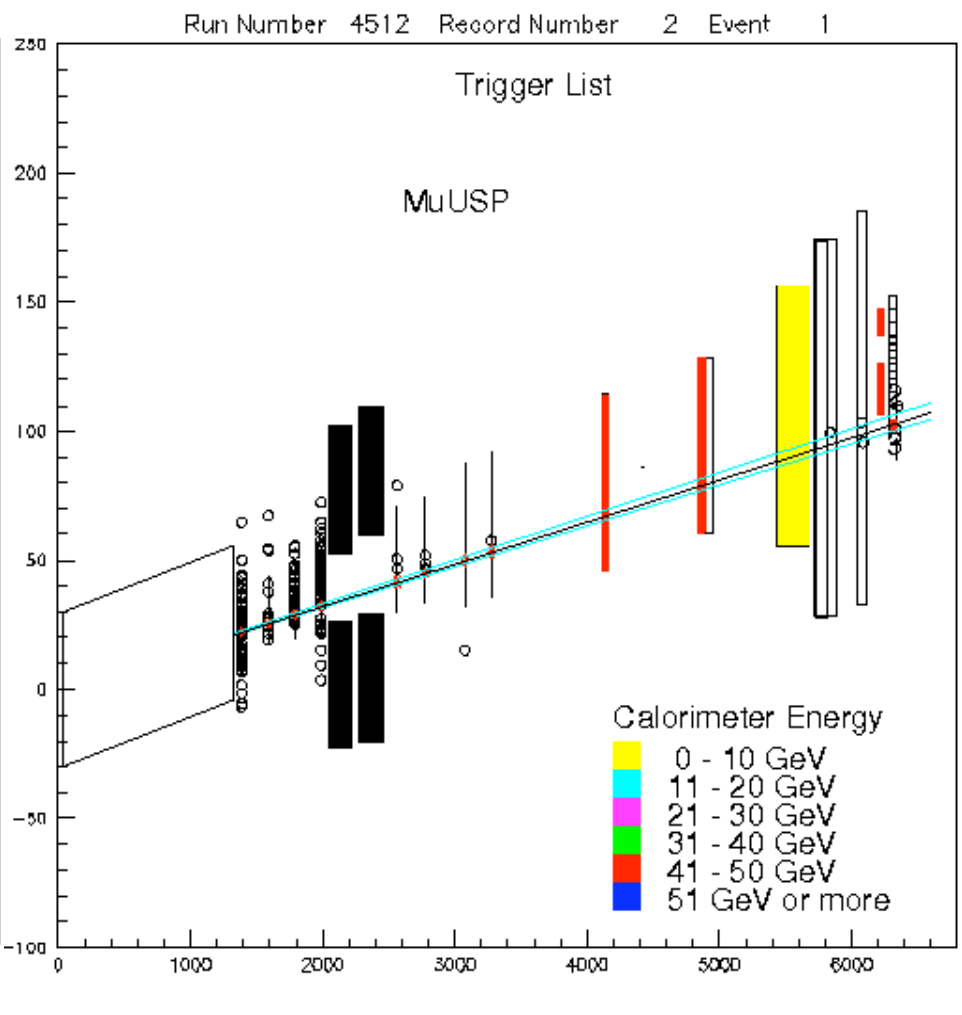
Search for $\Sigma^+ \rightarrow p\, e^+ e^-$ Decays

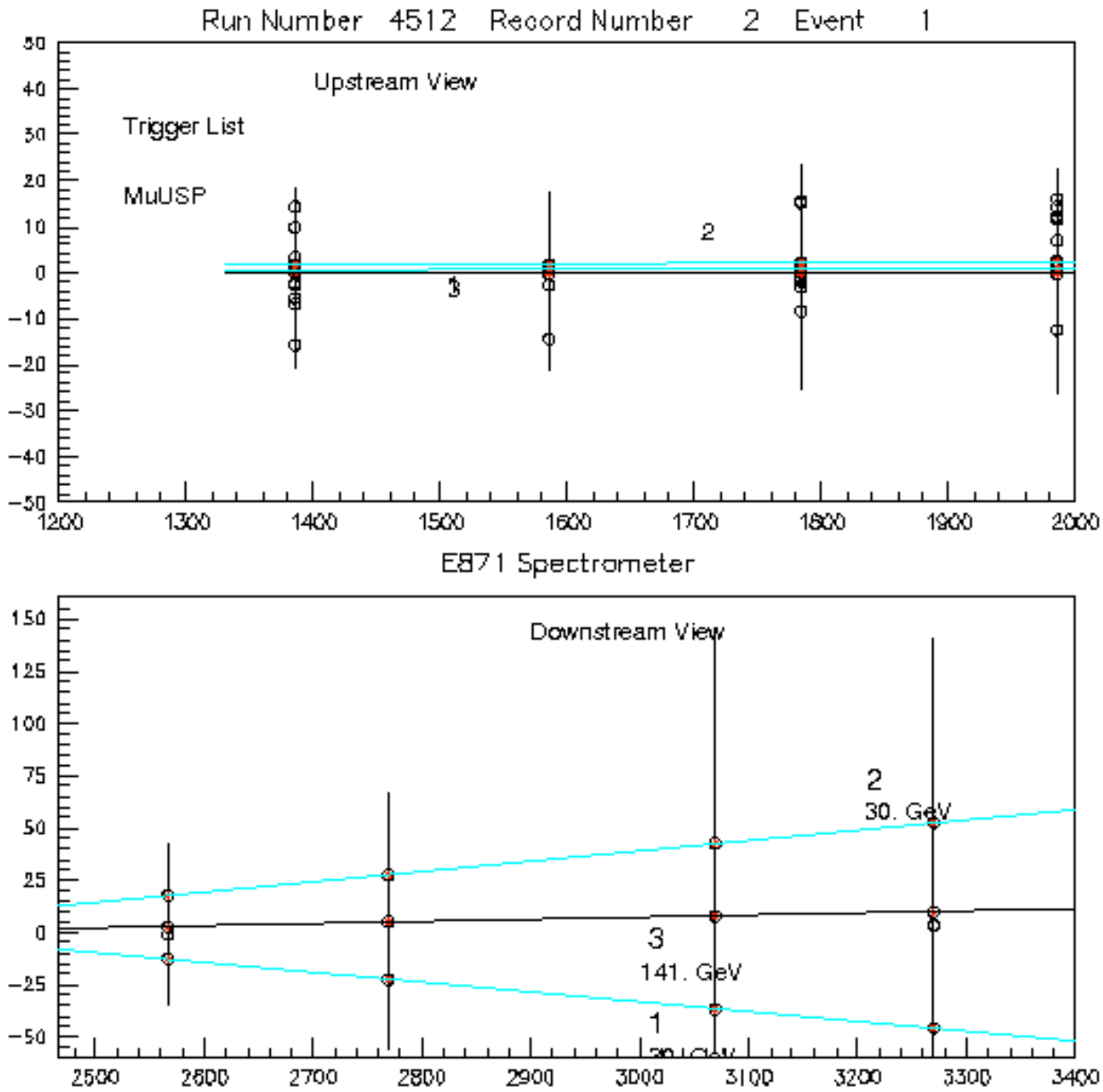


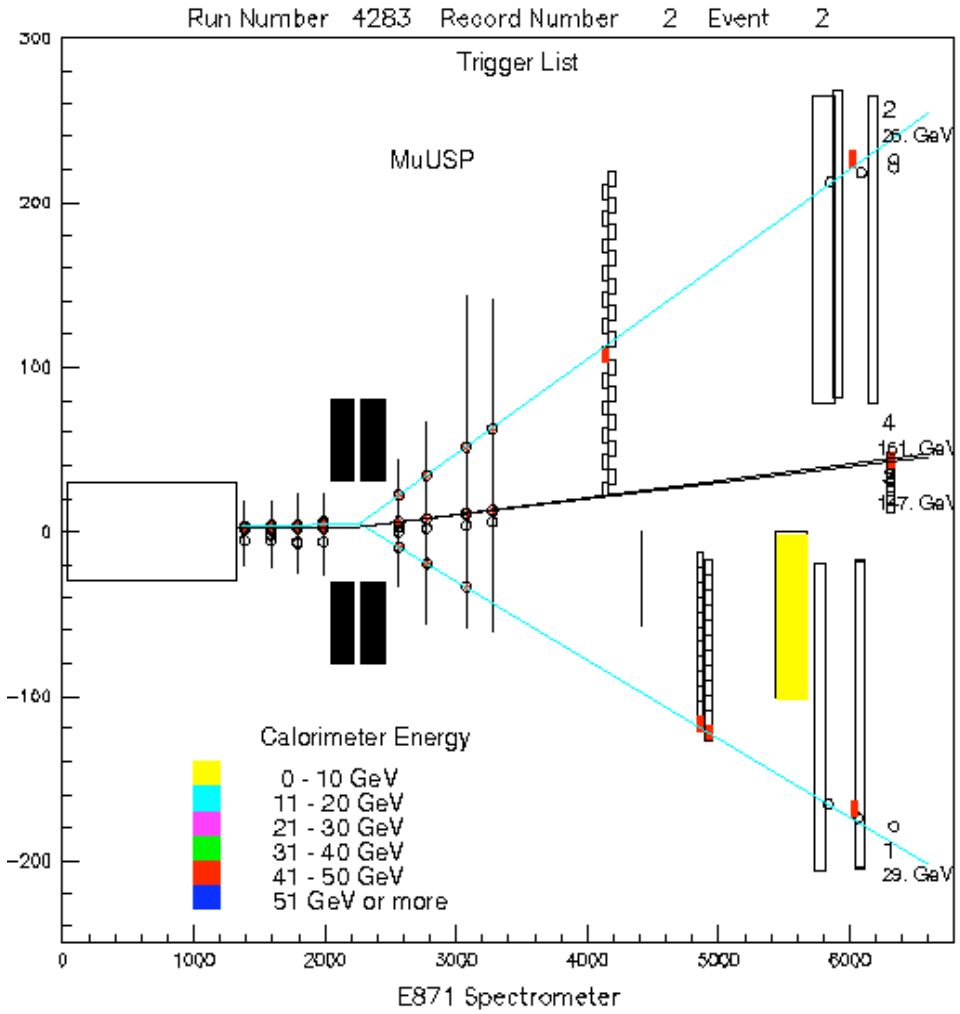
Assumption: $B(\Sigma^+ \rightarrow p\, e^+ e^-) = 3.9 \times 10^{-6}$

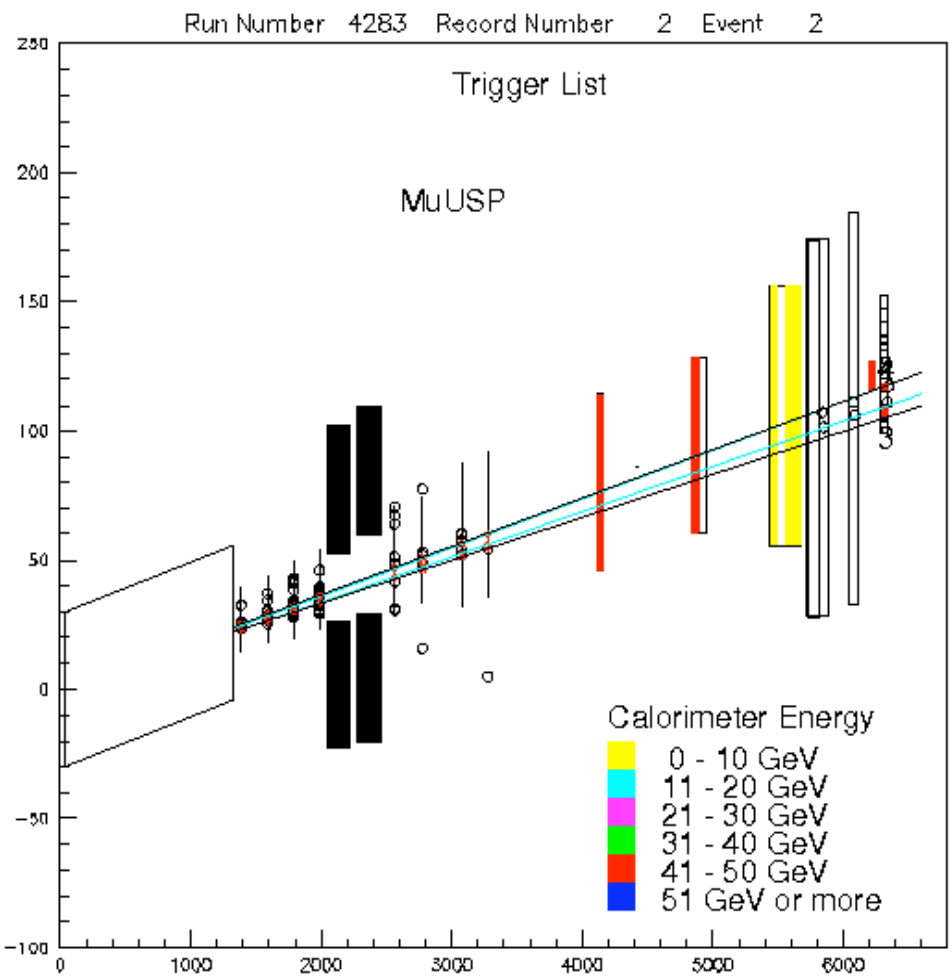
Event Variable	Event A	Event B	Event C
$M_{p\mu\mu}$	1190.15	1189.42	1189.63
$M_{\mu\mu}$	214.27	214.75	213.73
$M_{\pi\mu\mu}$	436.6	483.3	430.3
v_z	128.8	674.9	212.1
χ^2/ndf	1.27	1.16	1.30
DCA	0.18	0.15	0.22
Tgt-X	-0.068	0.21	-0.12
Tgt-Y	6.61	6.25	6.75
P_{μ}^{L}	29.77	25.77	28.15
P_{μ}^{R}	30.23	28.59	29.85
P_{prot}	141.55	146.15	135.26
P_{beam}	N/A	160.60	154.29
Tgt-X (beam)	N/A	0.07	0.28
Tgt-Y (beam)	N/A	6.65	6.26
$\chi^2/ndf\,(beam)$	N/A	10.2	8.91
N_{ss}	1	1	1
N_{os}	1	1	1
N_{beam}	1	2	2

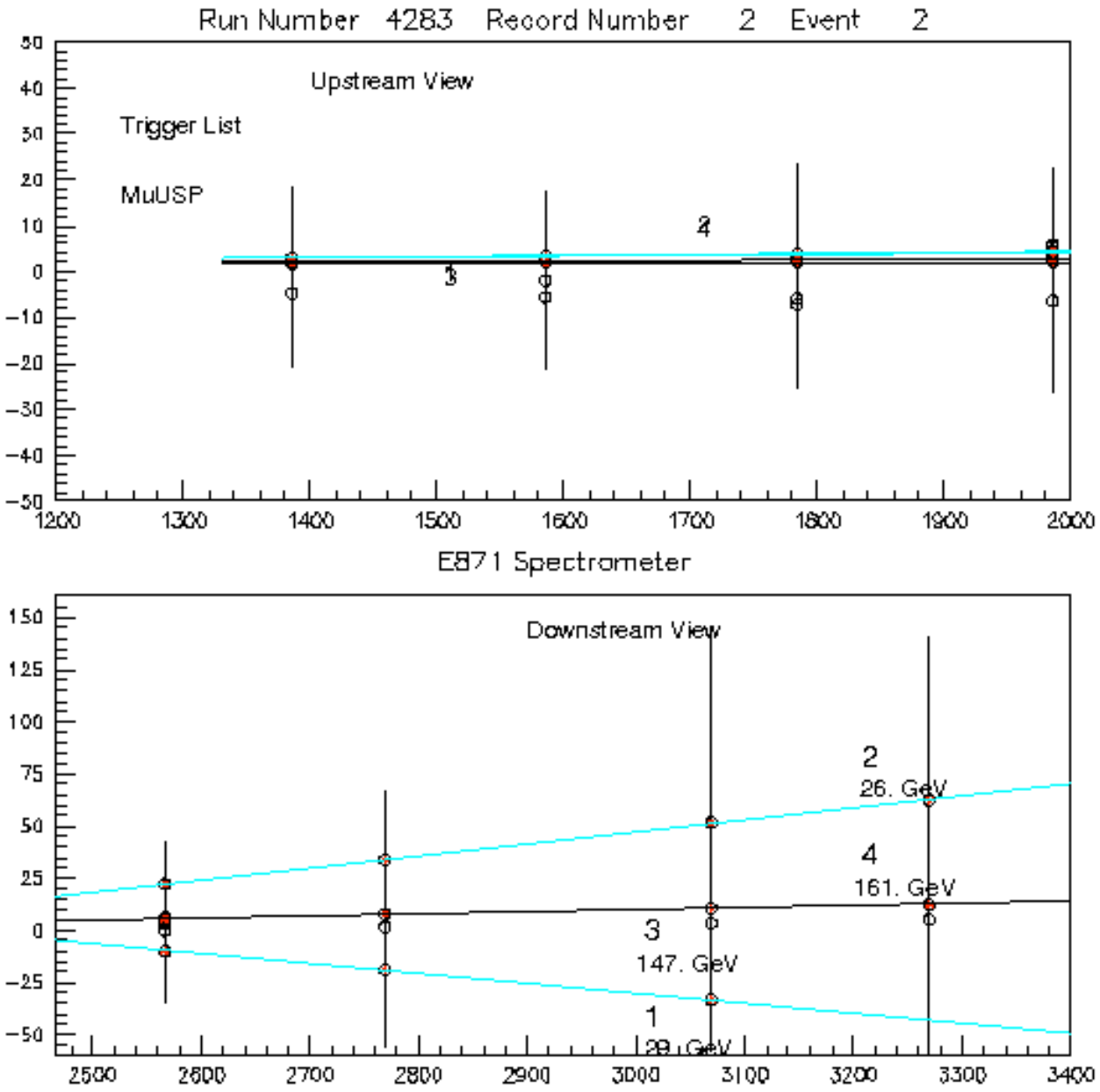

Run Number 4512 Record Number 2 Event 1
Trigger List
MuUSP
2
30. GeV
141. GeV
1
30. GeV
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more
E871 Spectrometer

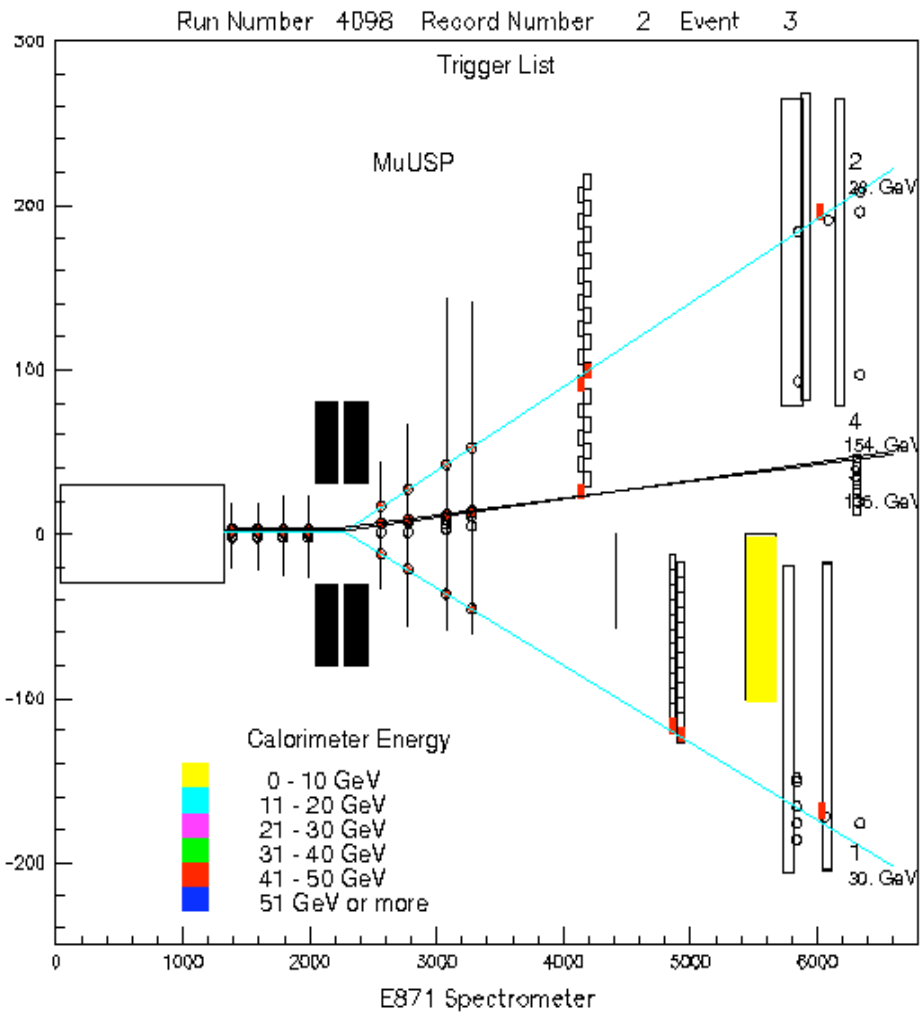

Run Number 4512 Record Number 2 Event 1
Trigger List
MuUSP
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more

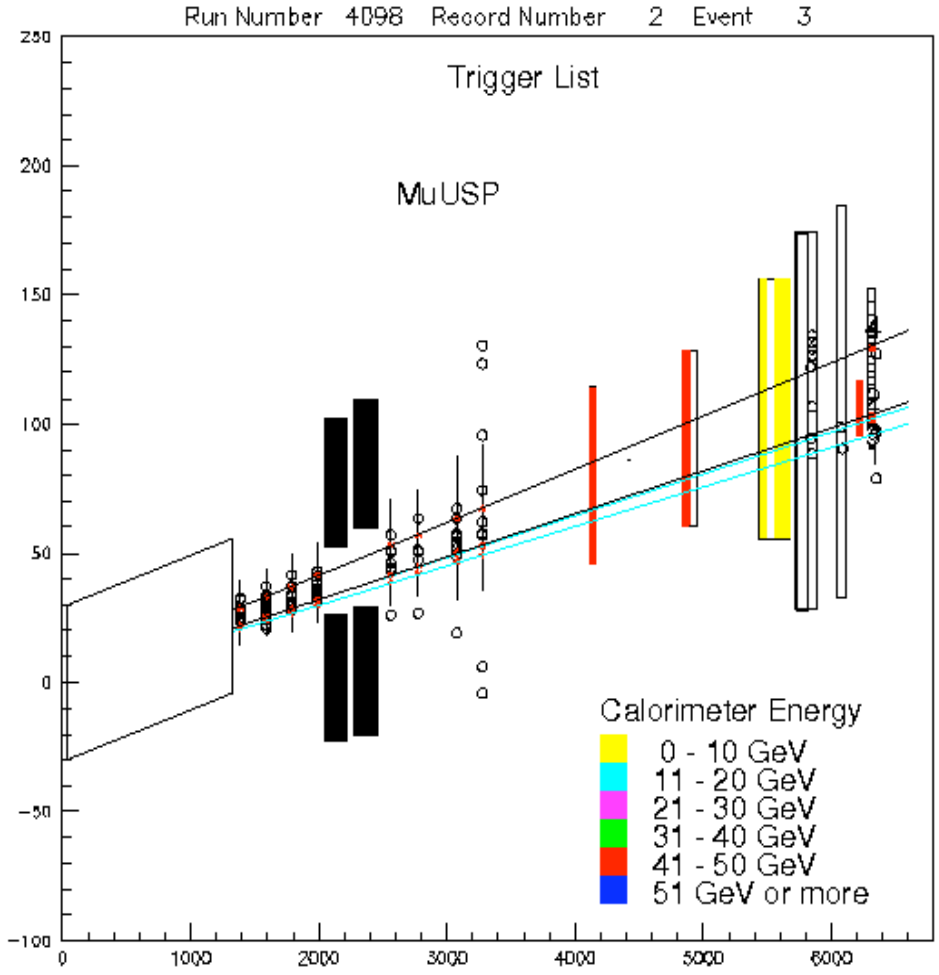

Run Number 4512 Record Number 2 Event 1
Upstream View
Trigger List
MuUSP
1
2
3
E871 Spectrometer
Downstream View
2
30. GeV
3
141. GeV
1

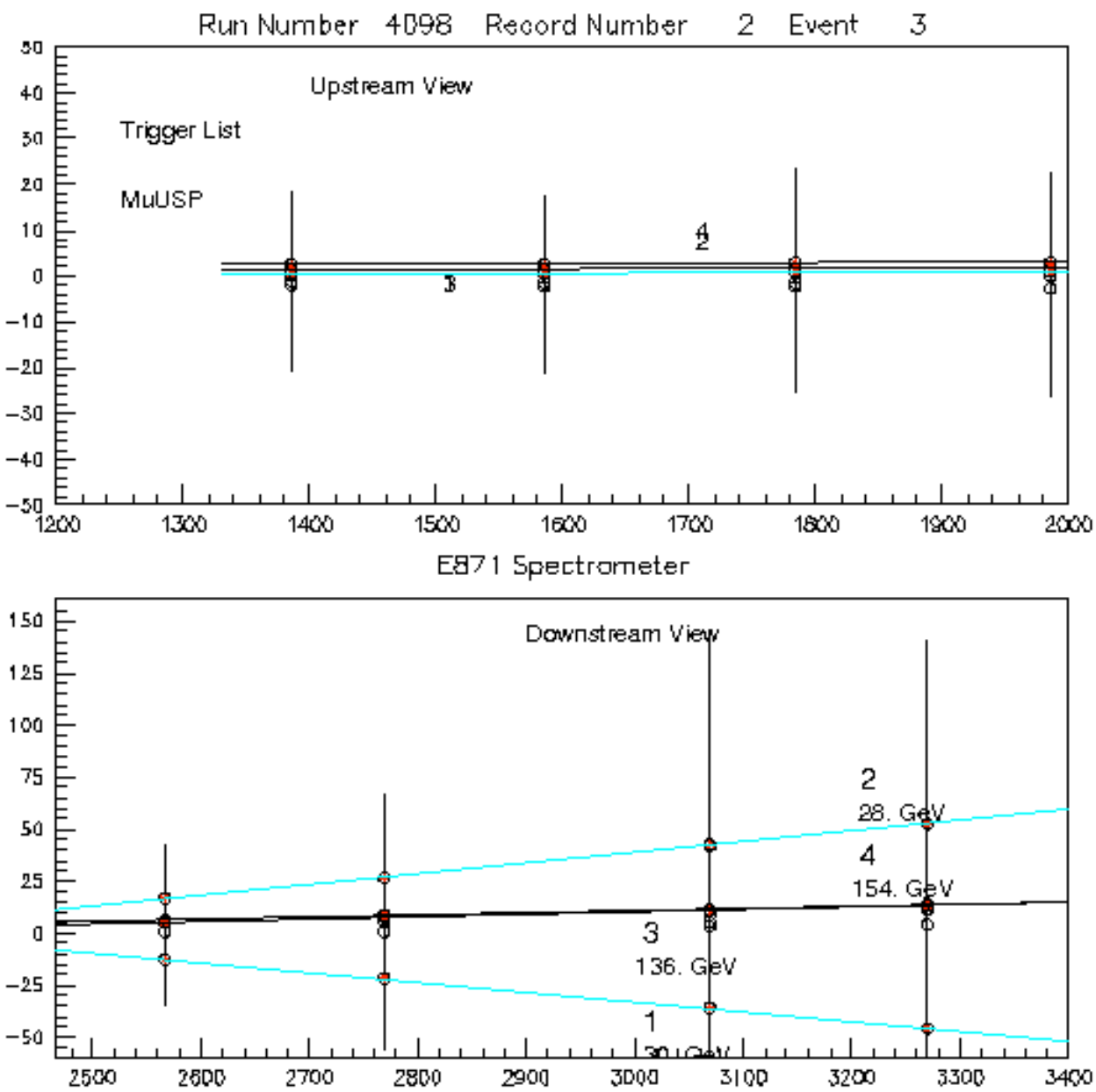

Run Number 4283 Record Number 2 Event 2
Trigger List
MuUSP
2
26. GeV
4
161. GeV
167. GeV
1
29. GeV
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more
E871 Spectrometer


Run Number 4283 Record Number 2 Event 2
Trigger List
MuUSP
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more


Run Number 4283 Record Number 2 Event 2
Upstream View
Trigger List
MuUSP
4
3
E871 Spectrometer
Downstream View
2
26. GeV
4
161. GeV
3
147. GeV
1
28. GeV


Run Number 4098 Record Number 2 Event 3
Trigger List
MuUSP
2
39. GeV
4
154. GeV
1
135. GeV
1
30. GeV
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more
E871 Spectrometer


Run Number 4098 Record Number 2 Event 3
Trigger List
MuUSP
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more


Run Number 4098 Record Number 2 Event 3
Upstream View
Trigger List
MuUSP
E871 Spectrometer
Downstream View
2
28. GeV
4
154. GeV
3
136. GeV
1